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AFRPL-TR-68-46

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ADVANCEMENT OF INJECTOR AND THRUST CHAMBER TECHNOLOGY

G. A. Voorhees, Jr.

TRW Systems Group

TECHNICAL REPORT AFRPL-TR-68-46

DECEMBER 1967

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GROUP-4

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AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTORATE OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

AF 04(611)-11382

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ADVANCEMENT OF INJECTOR AND THRUST CHAMBER TECHNOLOGY (u)

Total Pages 51

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TRW Systems Group

TECHNICAL REPORT AFRPL-TR-68-46

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FOREWORD

(U) This final technical report covers all work performed under Contract AF 04(611)-11382, Modification No. 3, "Advancement of Injector and Thrust Chamber Technology," dated 21 March 1967. The report was prepared by G. A. Voorhees, Jr., Project Engineer, Chemical Propulsion Technology Department. The test program was monitored by the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards, California (T. Chew, Project Engineer).

(U) This report contains results of a program of engine test firings of a centrally located, coaxial injector, rated at 250,000 lb_f thrust, in the throttled condition at the 50,000 lb_f thrust level.

(U) Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

T. J. C. CHEW
Chief, Combustion Technology Section
Liquid Rocket Division
Air Force Rocket Propulsion Laboratory

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SUMMARY

(U) An experimental test program to determine the scalability of the LMDE centrally located, coaxial injector to much higher thrust levels than previously tested has been completed. The experimental program was conducted generally in accordance with paragraphs 2.5, 2.6, and 2.7 of Exhibit "A" Technical Requirements of the aforementioned contract.

(U) The design of a nominal 250,000 lb thrust, 300 psia chamber pressure Thrust Chamber Assembly (TCA) capable of operating at a reduced thrust level of approximately 50,000 lb thrust was accomplished and fabrication using commercial, industrial fabrication techniques for the less critical components without precision tolerances was successful. The TCA design consisted of a centrally located coaxial injector and heat sink combustion chamber. The VETS B-1 test stand at Capistrano Test Site was modified to accept the TCA for firing tests.

(C) Fifteen test firings using N_2O_4/UDMH and totaling approximately 80 seconds of firing time were made during the test program. The influence of momentum ratio and mixture ratio on combustion efficiency (C*) of the centrally located coaxial injector was explored for two injector configurations. The initial test series (six firings) resulted in performance levels of 85 percent varying from a low of 82.5 percent at an oxidizer/fuel (O/F) ratio of 2.26 to a high of 85.5 percent at an O/F ratio of 2.76. The second test series (six firings) utilizing the modified injector resulted in achievement of approximately 95 percent combustion efficiency. Performance varied from a low of 92.3 percent at an O/F ratio of 2.50 to a high of 95.5 percent at an O/F ratio of 2.01.

(U) The dynamic combustion stability characteristics of the coaxial injector were experimentally evaluated in a large diameter combustion chamber. Two test firings employing nondirectional explosive charges to generate pressure surges were made. A 20-grain (TNT equivalent) explosive charge produced an "overpressure" in excess of 200 percent, which triggered a complex, high frequency acoustic wave. The acoustic wave was damped out in about 20 milliseconds with feed system recovery complete in about 40 milliseconds.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

SECTION I

INTRODUCTION

(U) This report is issued by TRW Systems pursuant to the requirements of Contract AF 04(611)-11382, Modification No. 3, "Advancement of Injector and Thrust Chamber Technology," dated 21 March 1967. The objectives of the program were to demonstrate the scalability of the LMDE coaxial injector, with respect to performance and dynamic combustion stability, to much higher thrust levels than had ever been run with this type injector. Additionally, it was intended to show that fabrication using commercial, heavy-industry fabrication techniques would result in acceptable hardware.

(U) The purpose of the program was to obtain the fundamental data necessary to provide a firm basis for scaling the LMDE coaxial injector design to multimillion-pound thrust, first-stage booster engines of maximum "cost-effectiveness." The first step in scaling the LMDE injector was a scale-up of 25-to-1, or a thrust level of 250, 000 lb_f. This size is great enough to determine if the injection principle is scalable with regard to both performance and combustion stability.

(U) Because of facility limitations at the TRW San Juan Capistrano Test Site (CTS) the program would employ full size hardware (approximately 3-1/2 foot diameter thrust chamber) but would operate at a reduced thrust level. This requires that the injector be throttled, a more severe requirement for the demonstration of high performance, without invalidating the demonstration of the combustion stability characteristics of the coaxial injector. This size hardware also makes it possible to investigate large rocket engine construction using commercial, industrial fabrication techniques with relatively few "precision" tolerances.

SECTION II

TECHNICAL DISCUSSION

1. ENGINE DESIGN AND FABRICATION

1.1 Design Approach

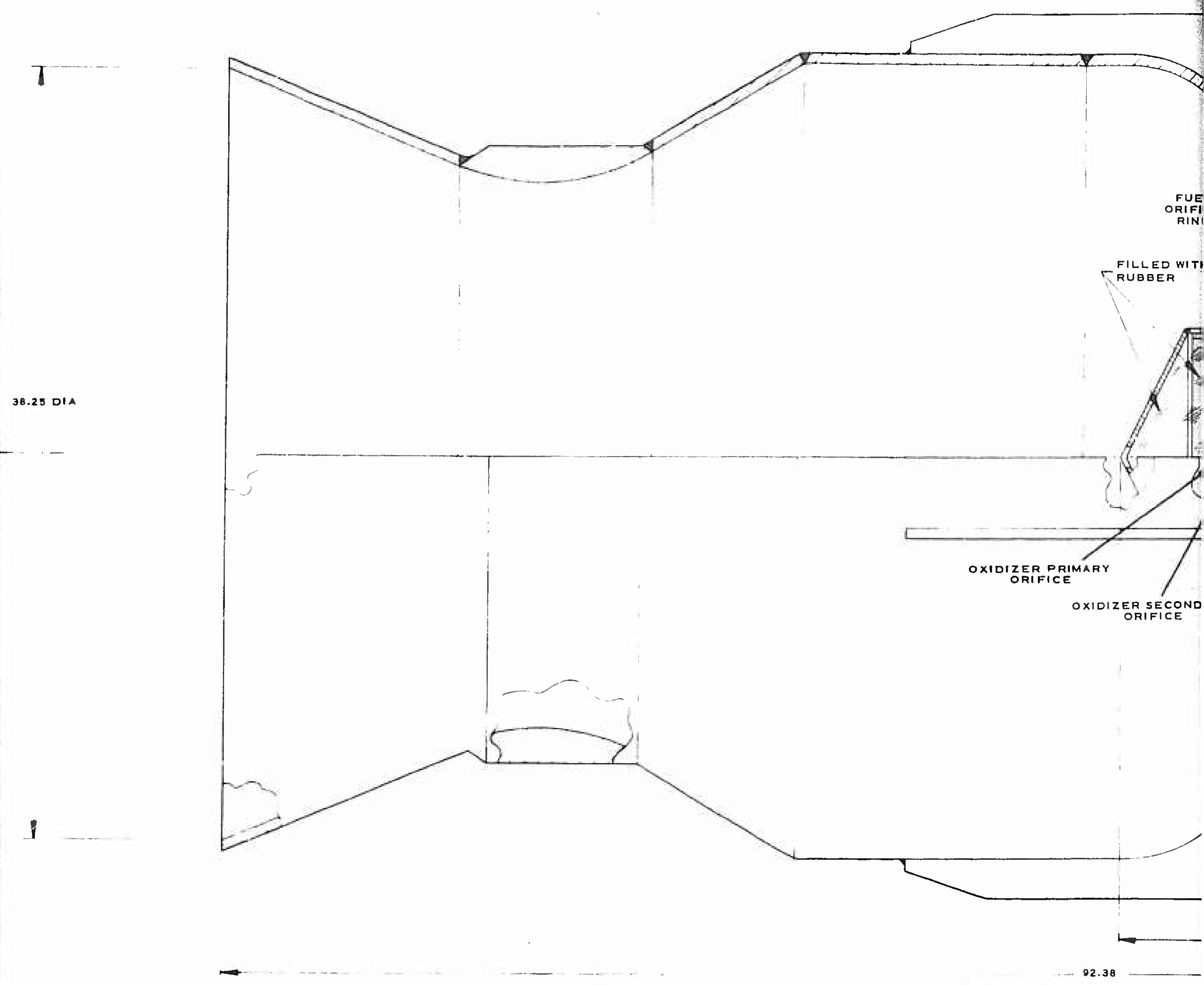
(U) TRW approached the engine design with the objective of minimizing both the recurring (production) costs and nonrecurring (development) costs. The engine is pressure fed, uses storable propellants (N_2O_4/UDMH) which are compatible with conventional materials of construction and for flight-weight versions would employ a sacrifical liner in a steel thrust chamber shell. The engine utilizes a centrally located, coaxial injector which has demonstrated high performance and inherent dynamic combustion stability at thrust levels of 10,500 pounds and less. The coaxial injector had been scaled previously over a 20-to-1 range (525 to 10,500 lb_f).

1.1.1 250,000 lb_f Thrust Static Test Engine Design

(U) The design of the static test engine fired in this test program is shown in Figure 1 and the actual engine (including thrust mount), as fabricated, is shown in Figure 2 during installation in position B1 of the Vertical Engine Test Stand (VETS) at the TRW San Juan Capistrano Test Site (CTS). The static test engine consists of two major assemblies — the centrally located, coaxial injector and the uncooled thrust chamber. The static test engine thrust chamber is designed to operate as a simple heat sink chamber with a rating of 250,000 pounds thrust at 300 psia. Test firing durations are therefore limited by the heat-sink capacity of the chamber. Facility limitations at CTS, primarily feed system and main support structure, required that the engine be operated at a maximum of 50,000 pounds thrust. This resulted in thrust chamber operation at a nominal chamber pressure of 60 psia.

1.1.2 Component Design — Injector Element

(U) The centrally located injector element, which was fabricated using industrial fabrication techniques, is shown in Figure 3 prior to start of hydraulic testing. Fuel is admitted to the injector element through a single 5-inch flanged inlet on a toroidal manifold. Fuel flows from the manifold through eight 3-inch-diameter holes in the outer jacket, then over the weir and is injected into the chamber through a singular annular orifice. Oxidizer is admitted to the pintle tube through a single 8-inch-diameter flanged inlet at the head-end of the engine. The primary oxidizer injection orifices are keyhole slots; thirty-six of these primary slots are distributed around the oxidizer pintle tube with thirty-six rectangular secondary slots interspaced equally between the primary slots.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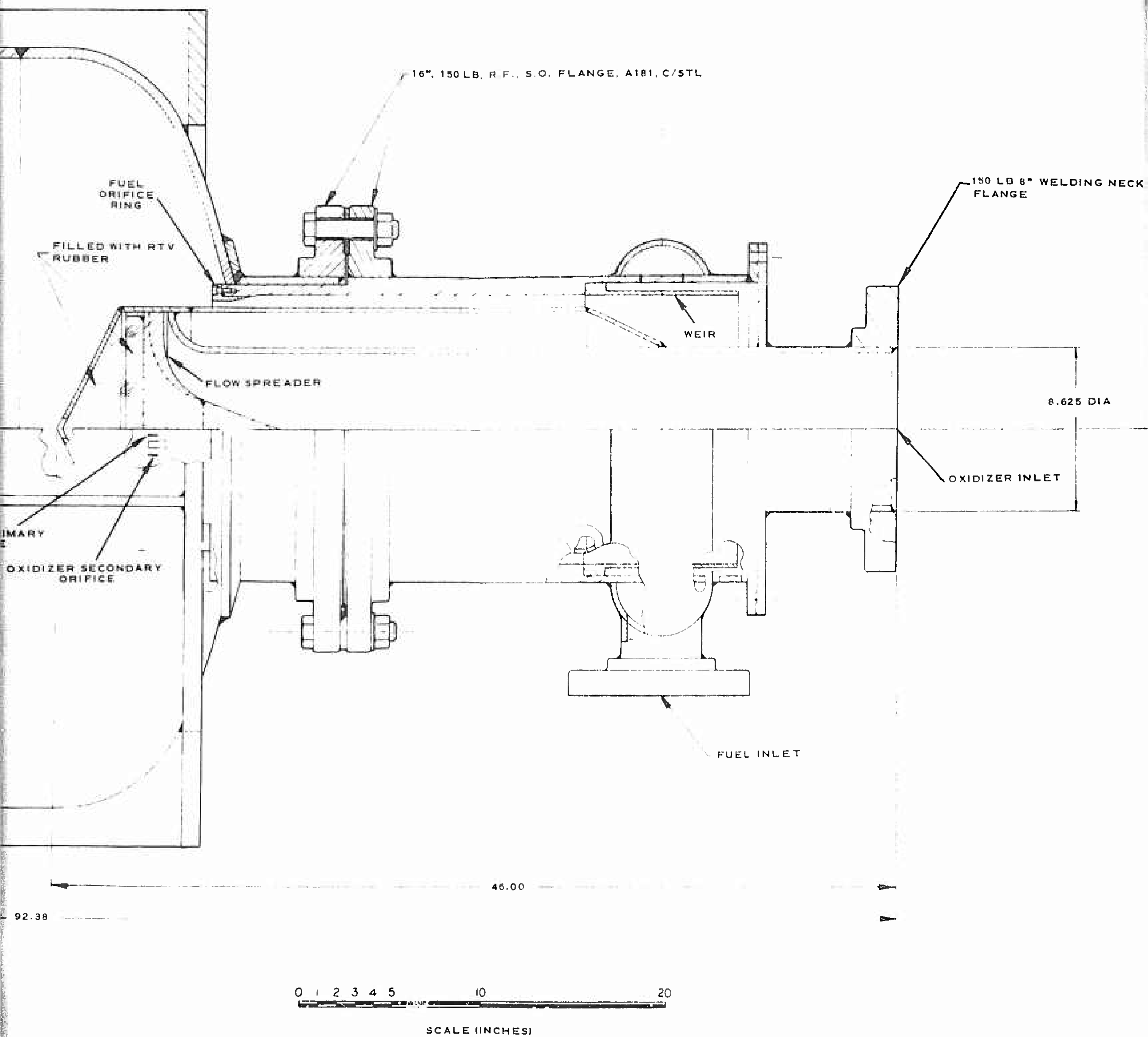

Figure 1. Static Test Engine Assem
250,000 lb_f Thrust
(SK401408 A)

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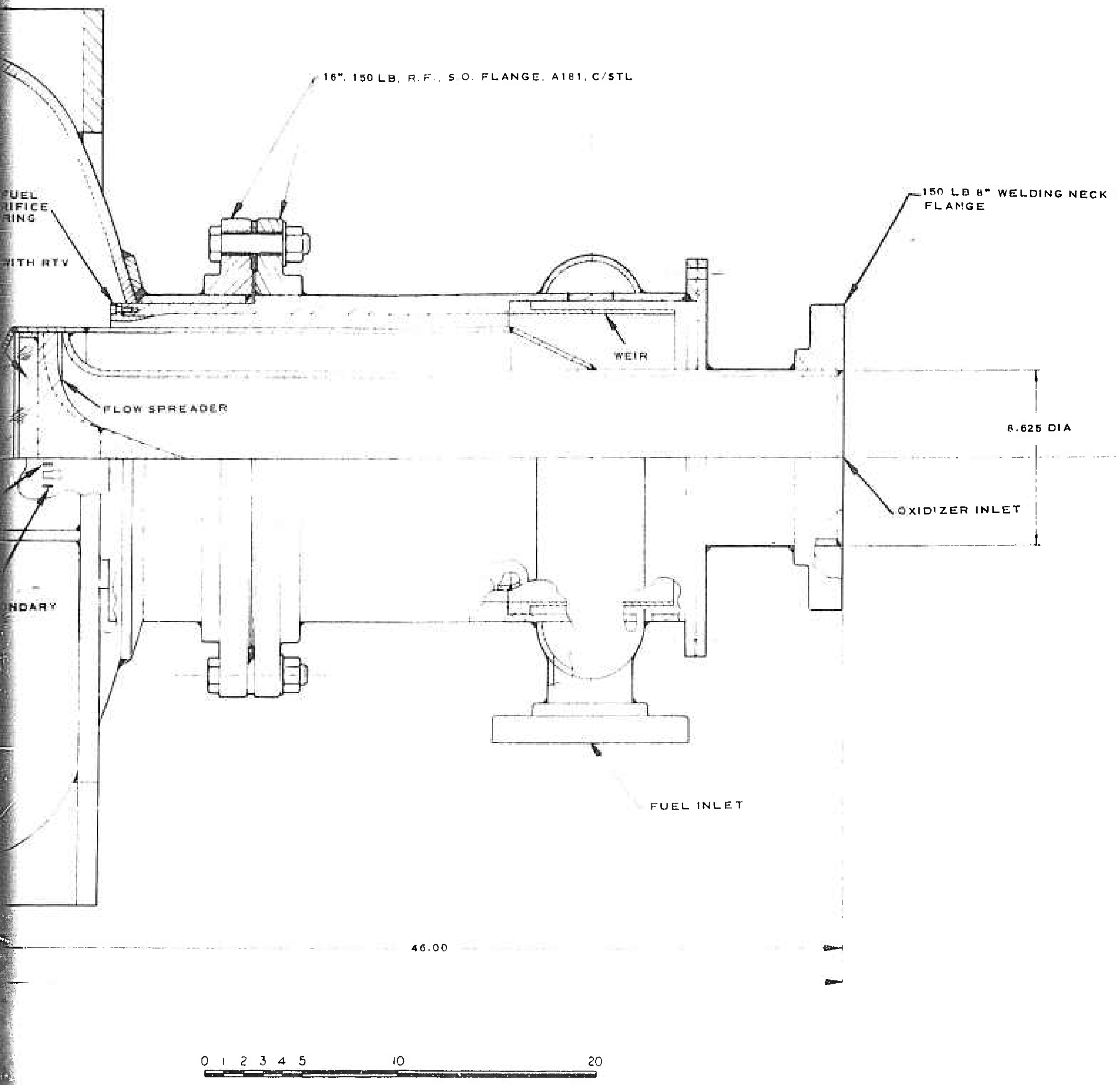

Figure 1. Static Test Engine Assembly 250,000 lb_f Thrust (SK401408 A)

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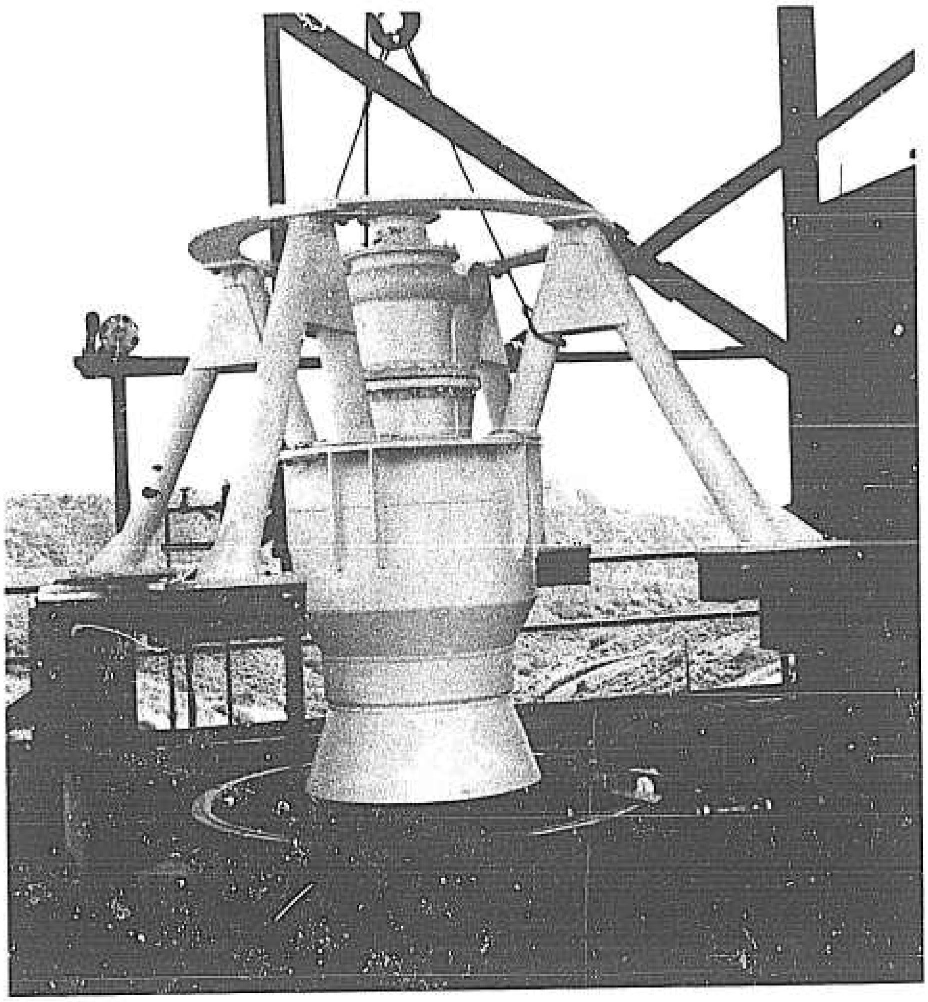

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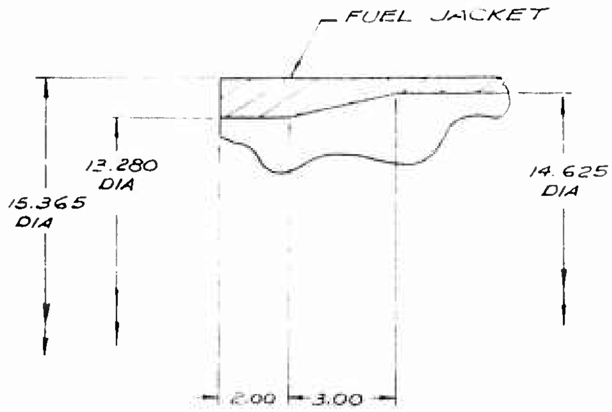
Figure 2. Photograph of Static Test Engine Installation

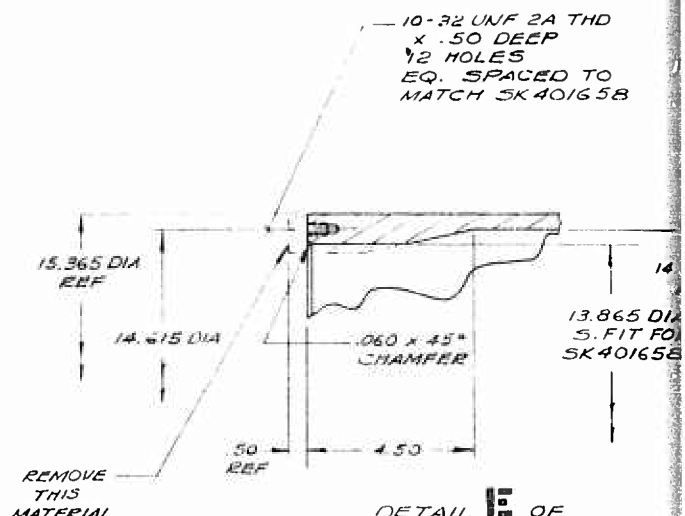
Figure 3. Coaxial Injector

(U) Since the flow passages and injector orifices are sized for 250, 000 lb_f flow rates it was necessary to throttle the injection orifices so that the desired injection ΔP's could be obtained at the reduced flow rates. The annular fuel orifice was fabricated with the required annular opening for the 250, 000 lb_f thrust fuel flow rate. A sleeve to fit over the oxidizer pintle tube was fabricated to reduce the fuel opening. This sleeve incorporated 12 support vanes to center the oxidizer pintle within the fuel jacket opening. Initial hydraulic testing of this configuration disclosed considerable discontinuities in the fuel sheet which were caused by the twelve support vanes. Therefore, the outer fuel jacket assembly was reworked as shown in Figure 4 to incorporate a replaceable fuel orifice ring. The orifice blank was made as shown in Figure 4 and the annular opening was varied by machining the I. D. of the orifice blank to the desired dimension.

(U) The oxidizer orifices are throttled by positioning the flow spreader within the oxidizer pintle tube to close off as much of the primary oxidizer orifices as desired, Figure 1. The orifice size and configuration were based on hydraulic test results of a previous model which was tested only at the full-flow position. Initial hydraulic testing of the injector indicated a greater discharge coefficient than that measured with the hydraulic test model. This required that the flow spreader be repositioned (blanking off more of the primary orifice) to obtain the desired injection ΔP. As a result, a higher percentage of the flow, nearly twice the design value, was injected through the secondary orifices.



DETAIL E OF SK401394 (EXISTING PART)



DETAIL E OF SK401394 (NEW PART)

-1	FUEL JACKET	
PART OR IDENTIFYING NO.	PART NAME	

QTY REQD PER ASSY CONFIGURATION

FINISH

HEAT TREAT

USED ON	NEXT ASSY	NEXT ASSY QTY REQD	APPLICABLE SPECIFICATIONS
APPLICATION			THE ABOVE REFERENCED TRW SYSTEMS SPECS FORM A PART OF THIS DRAWING

2 REWORK FUEL JACKET FROM SK 401394 INJECTOR ASSY AS SHOWN ON THIS SKETCH (NEW PART)

1. IDENTIFICATION MARKING IN ACCORDANCE WITH TRW SYSTEMS SPEC. PR 12-1 TYPE II CLASS 1G PART NUMBER

NOTES: UNLESS OTHERWISE SPECIFIED

1

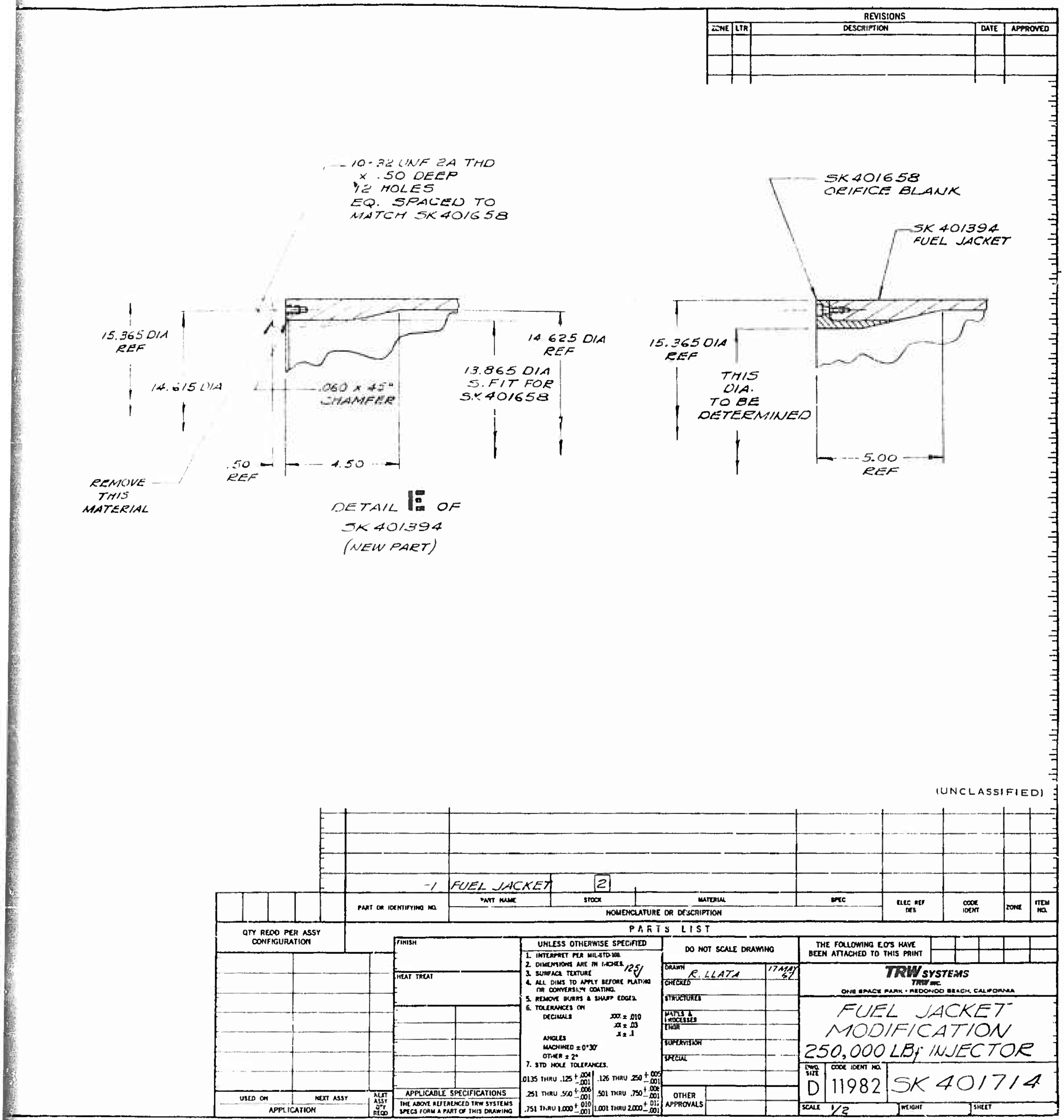


Figure 4. Fuel Jacket Modification 250,000 lb_f Injector

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(U) For injector configuration No. 2 a new flow spreader was machined which provided about 50 percent less flow through the secondary orifices than was obtained with injector configuration No. 1.

(U) The original injector configuration incorporated a silicone rubber pintle tip. The material employed for the pintle tip was Dow-Corning 20-103 which is a two-part room-temperature vulcanizing (RTV) material consisting of a silicone rubber base and catalyst. The DC20-103 silicone rubber base incorporates a mineral filler. There are no special preparations required for applying the insulating rubber. The surface to which the rubber is to be applied is prepared by cleaning and degreasing after which a coat of primer is applied to the surface. The two parts of the RTV material are then mixed and applied with a spatula. The material remains workable for approximately two hours and may be contoured as shown in the figure.

(U) Injector configuration No. 2 employed a conical steel pintle tip which was welded to the orifice sleeve. The void between the flow-spreader and pintle tip was filled with an RTV material.

(U) Fabrication of the injector was from commercially available carbon steel pipe and flanges which were assembled by welding. Only three specially machined parts were used in the assembly. They are: (1) oxidizer orifice ring, (2) flow spreader, and (3) fuel orifice ring. The parts were normally assembled by tack-welding with the final welds being made automatically on a submerged arc welder.

1.1.3 Component Design— Thrust Chamber

(U) Figure 5 is a photograph of the thrust chamber (with thrust mount) prior to assembly of the injector into the chamber. The design of the 250,000 lb_f thrust static test engine thrust chamber which was fabricated using industrial fabrication techniques, is shown in Figure 6. The thrust chamber has been designed to operate as a simple heat-sink chamber to permit test durations of 5 seconds continuous firing at the full thrust level without exceeding an external wall temperature of 600°F. These design conditions resulted in the selection of an 0.5-inch wall thickness material.

(U) A T-1 steel alloy was originally chosen for fabrication of the thrust chamber. A quoted 8-week delivery schedule for an elliptical dome of T-1 steel necessitated a change in material to 4130 alloy steel. The thrust chamber consists of an elliptical dome, a rolled and welded cylindrical section, a conical rolled and welded converging section, a machined throat section, and a conical rolled and welded expansion section. The injector support and attachment flange plus the thrust mount ring and support brackets were made an integral part of the thrust chamber.

(U) The chamber sections were joined together using tack welds with automatic submerged arc used for completion of all circumferential welds. All internal weld joints were ground smooth following the welding operation. No internal insulation was used in the thrust chamber.

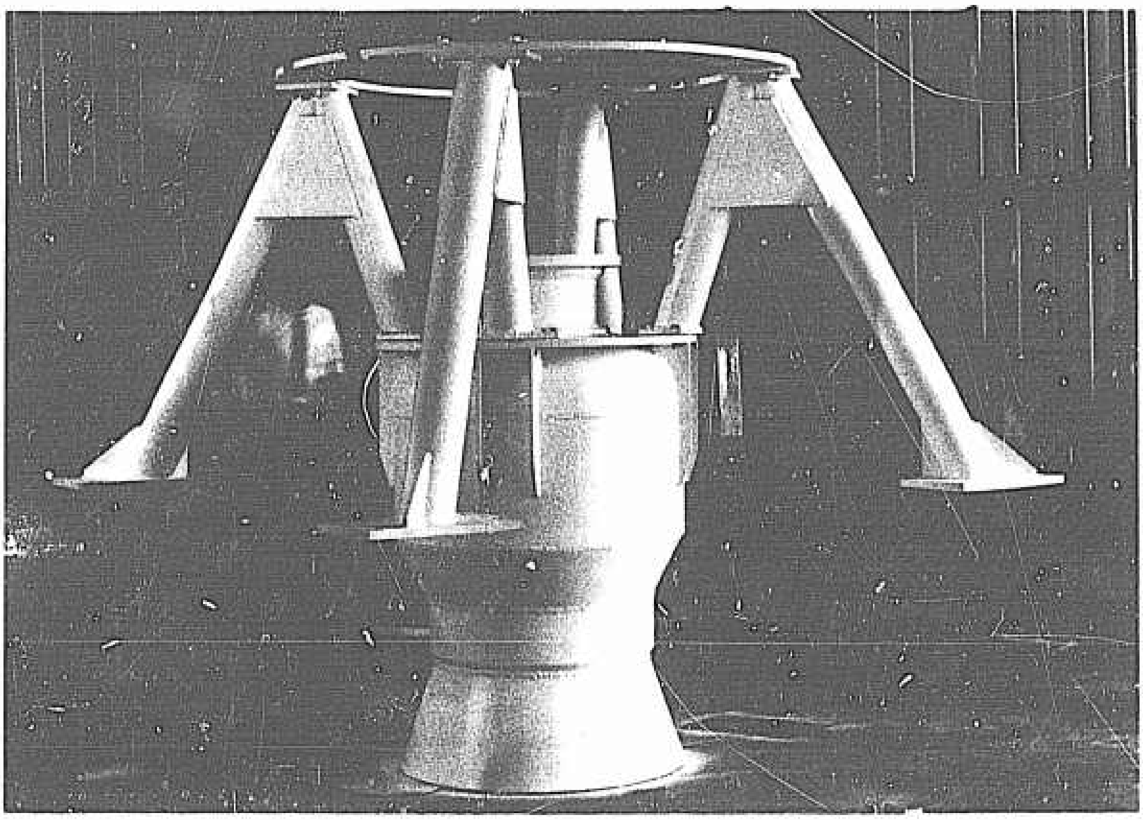


Figure 5. Thrust Chamber Prior to Injector Assembly

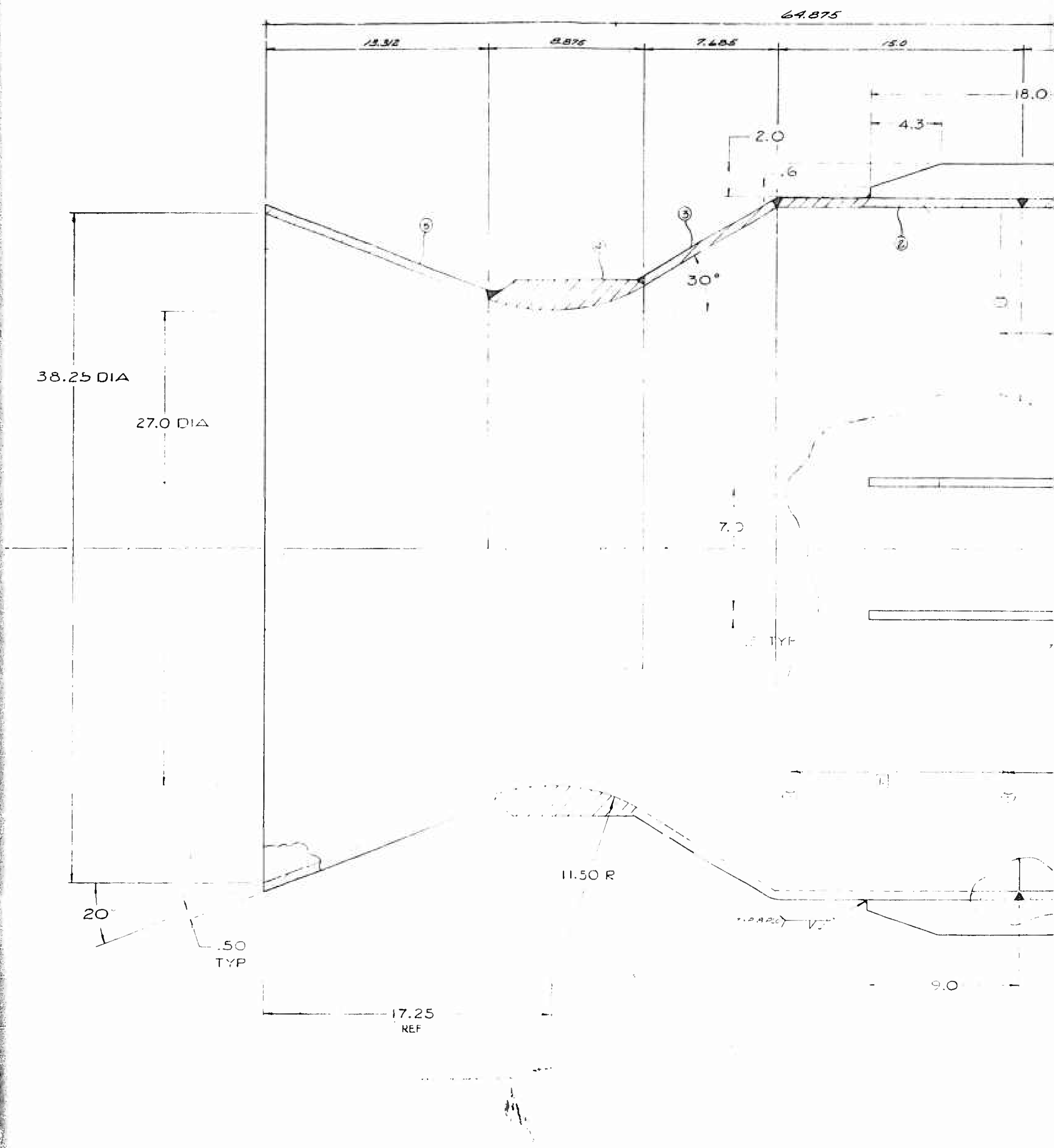
Fabrication of the injector, thrust chamber, and thrust mount was by J.C. Fabricators, Gardena, California. The test support machine shop at CTS finished-machined the oxidizer orifice ring and flow spreader and reworked the injector to incorporate the replaceable fuel orifice.

1.1.4 Component Design — Engine Controls

(U) Three-inch stainless steel Jamesbury ball valves, using modified Jamesbury pneumatic actuators, were utilized as engine shutoff valves. The shutoff valves were mated directly to the injector inlet reducers. An 8- to 3-inch reducer was used as a connection piece between the 3-inch shutoff valve and the 8-inch, 150 lb R.F.S.O. flange used as the oxidizer inlet. A 5- to 3-inch reducer was utilized on the fuel side. The shutoff valve sequence was controlled through microswitch circuitry to insure an oxidizer lead start and oxidizer lag shutdown. Cavitating venturis were installed in the propellant feed lines downstream of the stand position valves in order to limit the propellant flow rates and assure on-mixture ratio operation. Figure 7 shows the engine installed on VETS position B1 prior to the initial firing.

1.1.5 Instrumentation

(U) A detailed description of the instrumentation utilized during the testing, and the locations of the pickups are provided in Appendix II, page 38.



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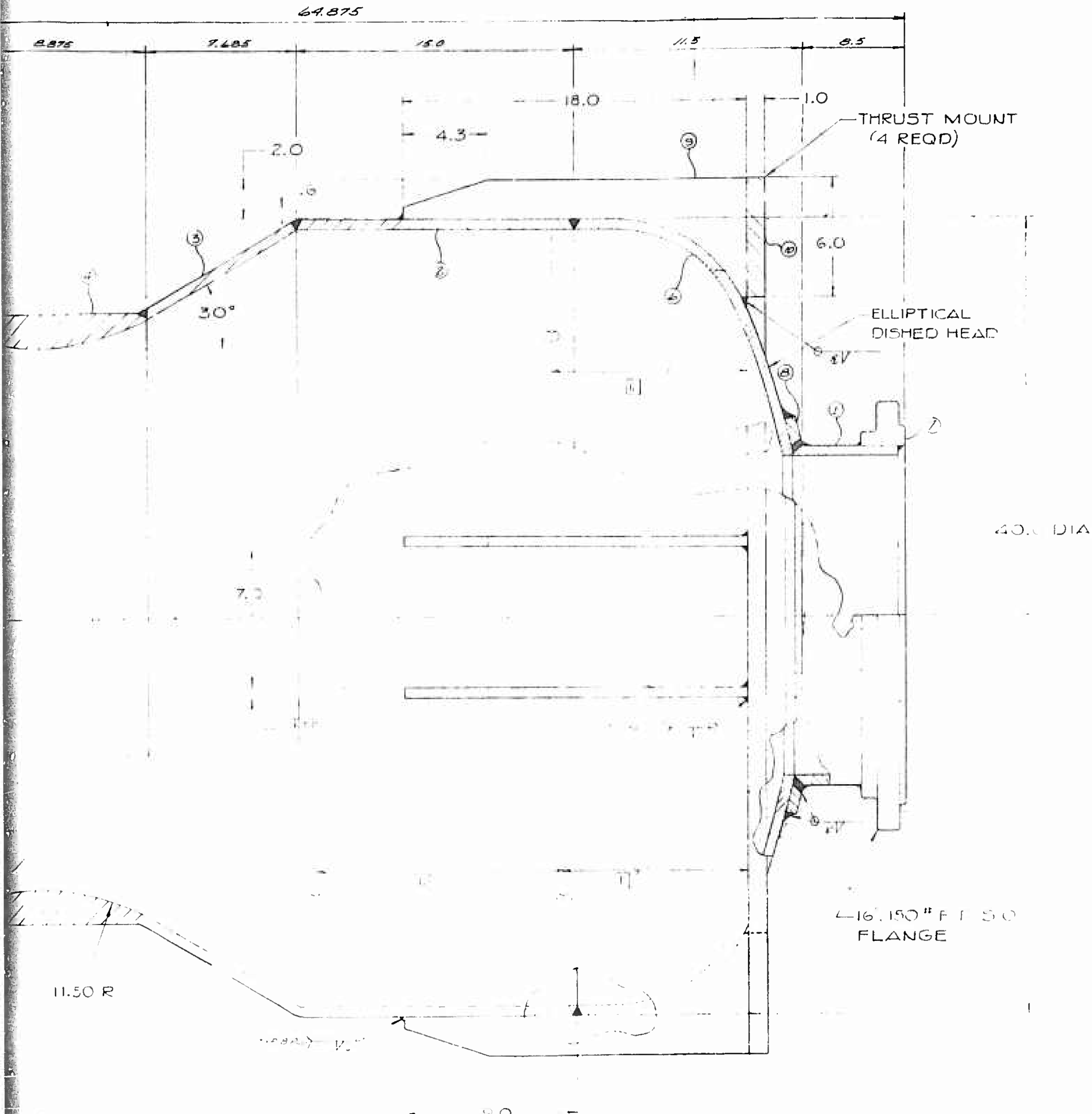

Figure 6. Compustion Chamber
250,000 lb_f Thrust,
Static Test Engine
(SK 401379 JC-1)

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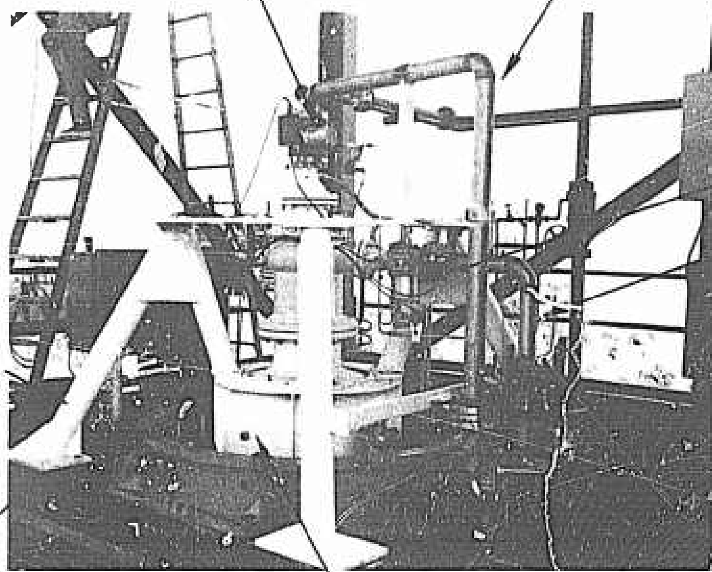

Figure 7. Engine Installation on VETS B1

2. VETS B-1 STAND MODIFICATION

(U) Paragraph 2.5 of the aforementioned contract specified the modification of Vertical Engine Test Stand (VETS) B-1 position at the Capistrano Test Site to accept the TCA for engine testing.

(U) VETS position B-. has been utilized as a 10,000 lb thrust sea-level test position on the LMDE development program. The major modifications to the test position included: (1) removal of all LMDE position equipment and fluid lines, (2) modification of the propellant feed systems to reduce pressure losses between propellant tankage and the engine, (3) installation of high pressure GN_2 storage trailers and high flow pressure regulators, and (4) fabrication of a 250,000 lb_f thrust mount.

(U) Utilization of the VETS B-1 position for this test program required complete removal of the LMDE thrust mount and load cell, the LMDE coolant water plumbing, the thrust ring firex plumbing, and the flush and purge plumbing. Modification of the propellant feed system required removal of the tank outlet filters, the 1-1/2 inch flowmeter loops, and the screen filter spool pieces downstream of the B-1 position valves. These items were replaced with 3-inch stainless steel spool pieces, 3-inch flowmeters with 3-inch outlet and inlet stainless steel sections, and 3-inch 90-degree elbows, respectively. A schematic of the propellant feed system is given in Appendix I.

(U) The complete propellant tank pressurization system was replaced with larger stainless steel piping and Series 400 Grove pressure regulators installed as close as possible to the propellant tanks. Mobile high-pressure GN_2 storage trailers (317.5ft^3 capacity) were placed adjacent to the test stand in order to provide sufficient GN_2 reserve. The individual trailers, one for oxidizer and one for fuel, were close-coupled plumbed to the Series 400 Grove pressure regulators.

(U) A four-legged thrust mount with legs connected with a circular ring was designed and fabricated to transmit thrust loads from the TCA to the stand structure. The thrust mount was bolted to thrust mount pads which were welded to the 36-inch-wide flange beams supporting the thrust ring in the test stand. A coolant water spray bar was installed at the exit plane of the nozzle to prevent overheating of the stand lower level wiring and plumbing.

(U) New GN_2 purge and H_2O flush systems were fabricated for both the oxidizer and fuel side of the injector.

3. PERFORMANCE EVALUATION

(U) As required in paragraph 2.6 of the contract (modification No. 3), two test series totaling twelve short duration hot-firing tests were made at a nominal thrust level of 50,000 pounds and a nominal chamber pressure level of 65 psia. These two test series experimentally explored the influence of momentum ratio, mixture ratio, and chamber pressure on combustion efficiency (as determined by C* measurements). Hydraulic testing of the injector to determine the injection spray pattern for correlation with hot-firing test results preceded the firing of each injector configuration.

3.1 Hydraulic Testing — Initial Injector Configuration

(U) Following completion of the engine installation on VETS B-1 the coaxial injector was removed from the TCA and installed on the Propulsion Integration Test Stand (PITS) for hydraulic testing. Preliminary hydraulic testing of the injector indicated unacceptable hydraulic characteristics (streaking) of the cylindrical fuel sheet. This characteristic was caused by the 12 vanes used to center the pintle tube (flowing oxidizer) within the fuel orifice. In addition, the measured oxidizer injection ΔP was considerably lower than expected in the throttled position. This was attributed to a higher than anticipated discharge coefficient (C_d) in the throttled position.

3.1.1 Injector Configuration No. 1

(U) In order to eliminate the streakiness caused by the 12 support vanes the fuel jacket was redesigned to incorporate a replaceable fuel orifice ring. The pintle tube was then centered within the fuel orifice through use of set screws upstream of the fuel orifice. Hydraulic testing of the injector was resumed following completion of the injector rework. Figures 8 and 9 show the injector oxidizer streams being hydraulically tested separately and in combined flow with the fuel sheet,

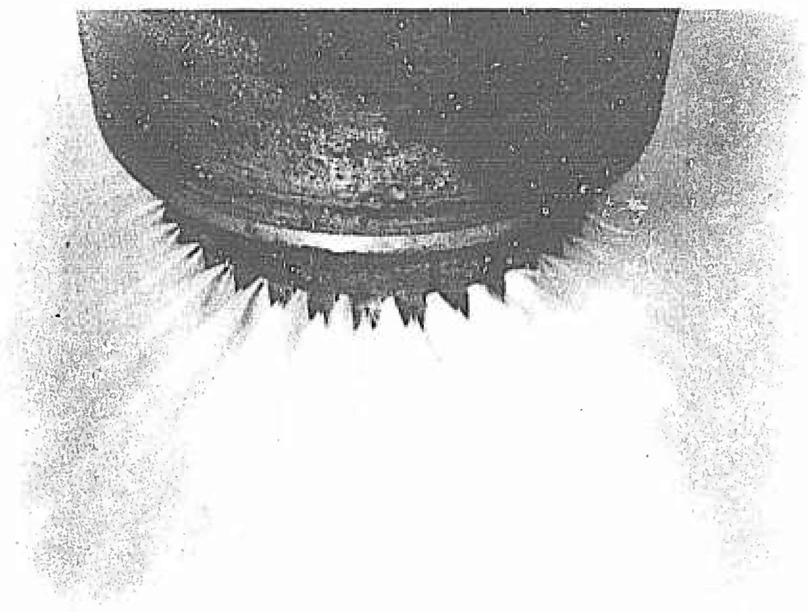

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Figure 8. Oxidizer Flow Pattern, Injector Configuration No. 1

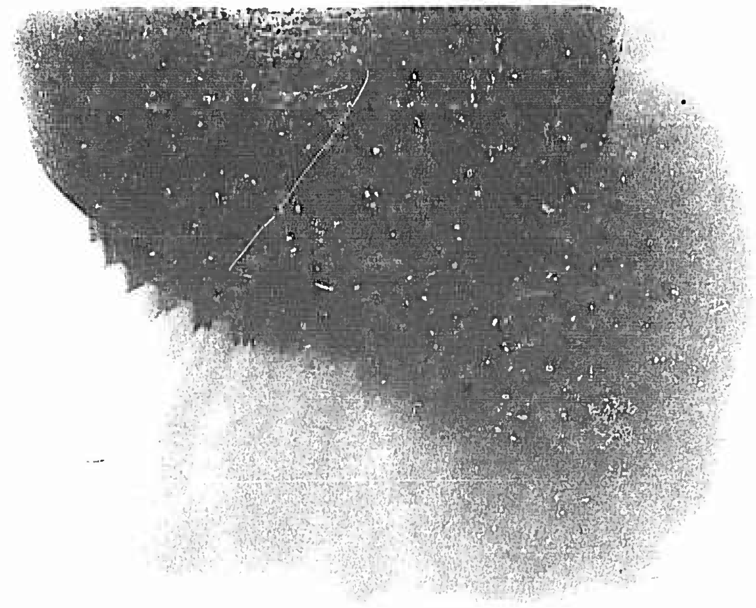

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Figure 9. Combined Flow Pattern, Injector Configuration No. 1

respectively, prior to the first engine firing. The hydraulic test ΔP data is shown as Figure 10. As previously noted the secondary oxidizer injection area for this configuration is nearly twice the area expected. This condition resulted from the additional throttling of the primary orifices to achieve the desired injection ΔP.

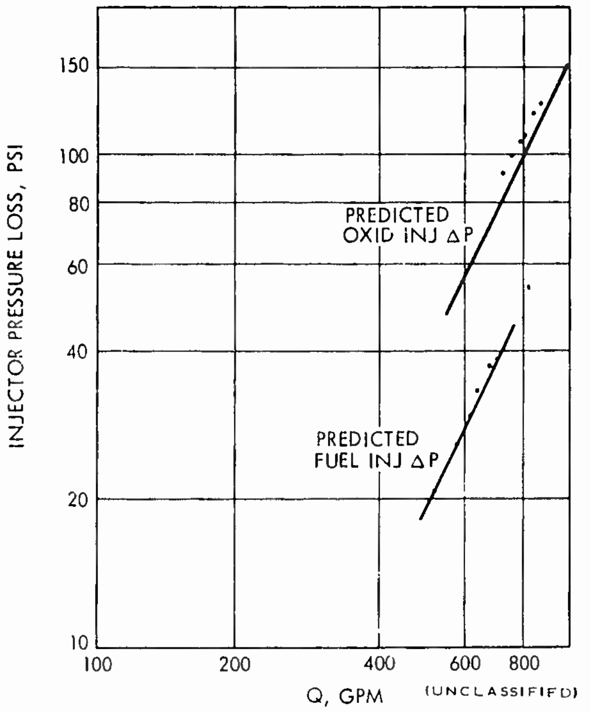

Figure 10. Hydraulic Test Data, Injector Configuration No. 1

3.1.2 Injector Configuration No. 2

(U) Examination of the data from test series No. 1 (VB-1-581 through VB1-586) showed insufficient penetration of the fuel sheet by the oxidizer filaments. The exhaust flame showed a fuel rich mantle covering a more oxidizer rich core. The performance data (as defined by C* measurement) indicated an increase in performance for decreasing momentum ratio (F/O). Therefore, two modifications were made to the injector following test firing VB1-586; the injector was then resubjected to the hydraulic flow characterization tests. Figure 11 shows the ΔP data as a function of volumetric flow rate while Figure 12 shows the combined oxidizer flow and fuel flow prior to test firing VB1-587. The secondary flow for this configuration is about 50 percent of the flow (secondary) employed on injector configuration No. 1.

3.2 Engine Testing

(U) Following the hydraulic characterization testing of injector configuration No. 1 the injector was reinstalled in the TCA and feed lines were reconnected. Several system blowdown tests (H_2O/H_2O and H_2O/N_2O_4) were made prior to the initial firing to verify system pressure loss characteristics. During the system blowdown tests it became obvious that a 3-second duration firing would not result in stabilized performance data. The fire valve sequencing, flow limited by cavitating venturis, and large manifold fill volumes resulted in injector prime times of nearly two

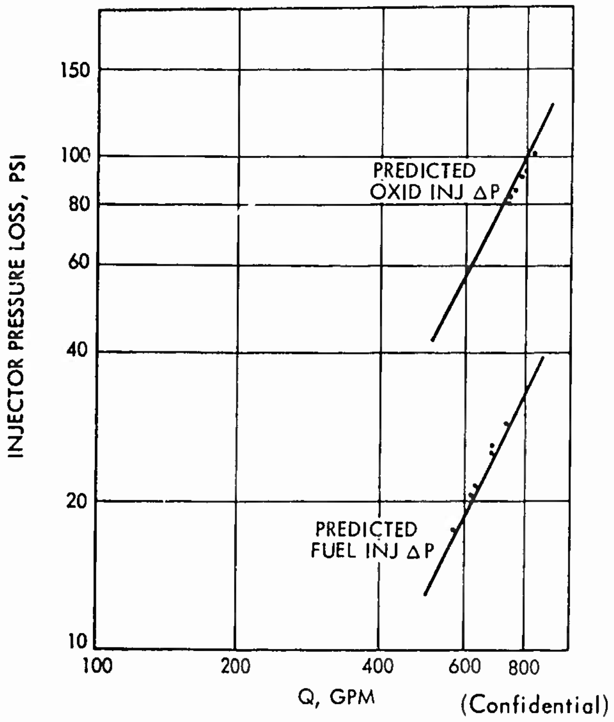

Figure 11. Hydraulic Test Data, Injector Configuration No. 2

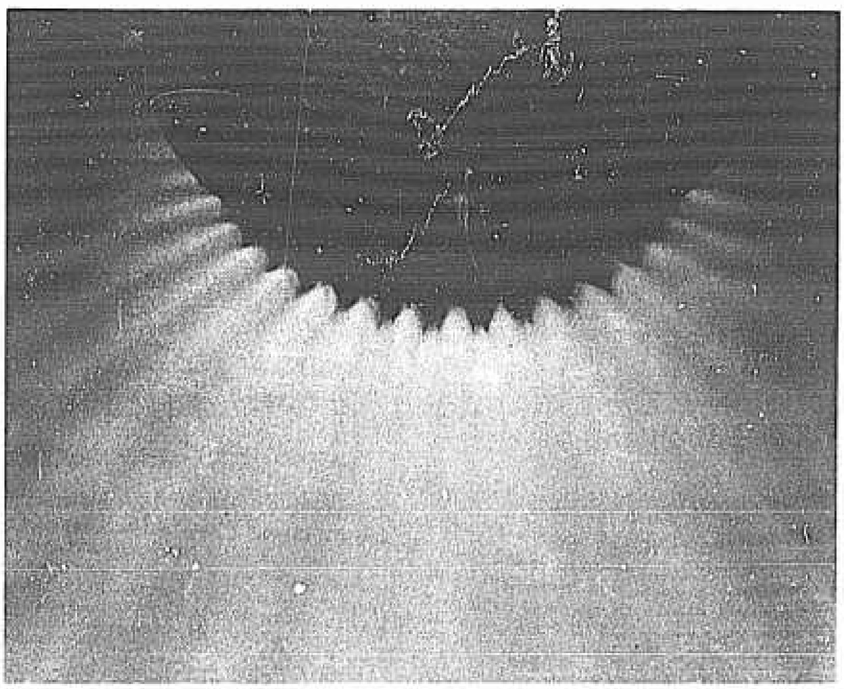

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Figure 12. Combined Flow Pattern, Injector Configuration No. 2

seconds at the reduced flow rates. Therefore, the duration of the initial test firing requested on the Propulsion Test Request (PTR 9823-002) for a start transient test firing was increased from 0.5 to 1.0 second to 3.0 seconds. The initial test firing made was at a targeted oxidizer fuel (O/F) ratio of 2.25, a total flow rate of 220 pounds per second, and a firing duration of 3.0 seconds. The data for both Performance Evaluation test series is tabulated in Table I and plotted as Figure 13. Pertinent remarks for each test series are given in the following paragraphs.

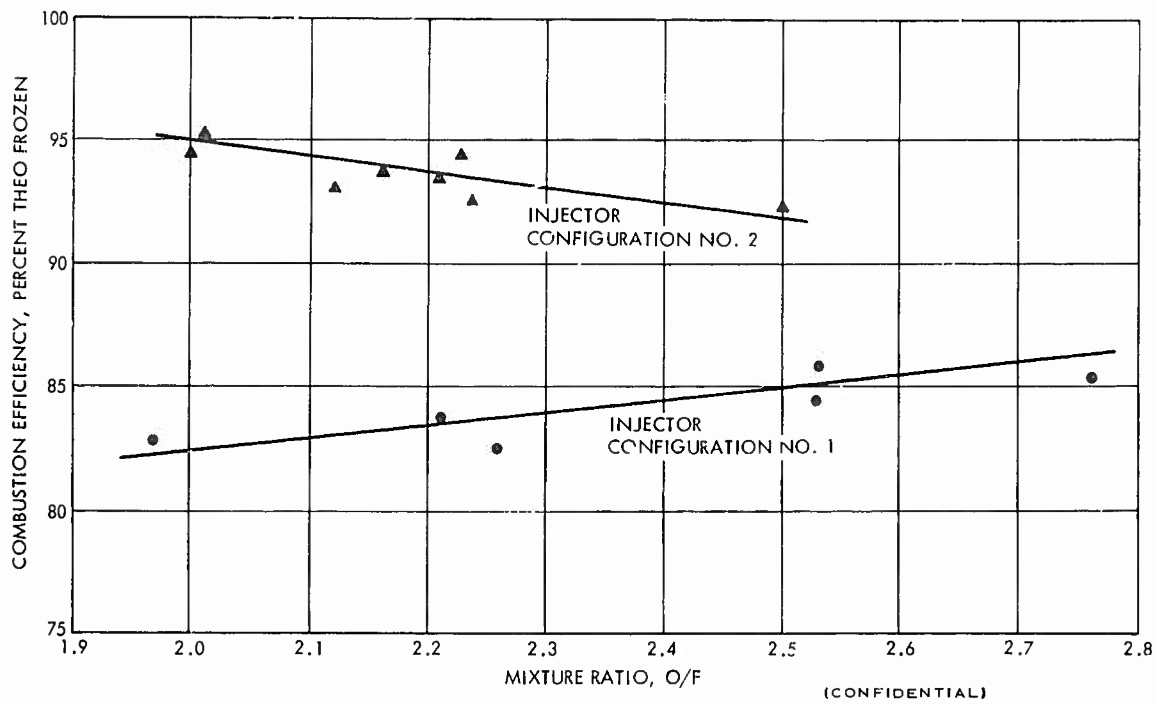

Figure 13. Engine Performance Data

3.2.1 <u>Test Series No. 1</u>

(C) As shown in Table I the initial test series consisted of four firings at the design weight flow rate and covered the O/F ratio from 1.97 to 2.76, plus two firings at 110 percent of design flow rate and selected O/F ratios. Appendix IV contains pertinent remarks and observations for each test firing in the test series. Observation of the exhaust flame and the low performance (about 85 percent) indicated that there was insufficient penetration of the fuel sheet by the oxidizer filaments. The fuel rich mantle covering a more oxidizer rich core was evident in the exhaust flame. In addition, performance increased as the O/F ratio was increased at the same total weight flow rate. Based on these observations after the initial three firings, the decision was made to make two modifications to the injector. These modifications were:

1) Fabricate a new flow spreader to reduce the amount of secondary flow.

2) Decrease the fuel injection velocity by increasing the annular fuel opening.

Table I. Coaxial Injector Scaling Studies Engine Test Summary

Date	Time	Test Series	Run No.	Inj Conf.	W_t (lb/sec)	O/F	P_{ch} (psia)	P_{cd} (psia)	P_{ns} (psia)	ΔP_{io} (psi)	ΔP_{if} (psi)	C* Test (ft/sec)	η_c* (%)	Run Time (sec)
6-7-67	1950	1	VB1-581	1	216.6	2.26	52.0	49.9	52.6	101.4	29.2	4474	82.5	3.2
	2355	1	582	1	220.7	2.53	53.6	51.2	54.1	108.6	25.6	4509	84.5	5.3
6-8-67	0020	1	583	1	215.1	2.76	52.3	49.9	52.6	108.3	21.3	4506	85.5	5.3
6-9-67	0125	1	584	1	219.7	1.97	53.3	51.2	54.1	93.0	37.6	4530	82.8	4.5
	0155	1	585	1	245.0	2.21	60.0	57.3	60.5	121.7	38.3	4543	83.8	4.5
	0230	1	586	1	243.1	2.53	59.8	57.2	60.4	128.1	33.8	4570	85.9	9.5
6-14-67	2310	2	VB1-587	2	218.9	2.16	60.5	57.3	60.5	82.7	21.5	5085	93.7	5.6
	2355	2	588	2	223.0	2.50	59.4	56.4	59.5	92.2	17.9	4920	92.3	5.2
6-15-67	1050	2	589	2	224.4	2.01	63.7	60.3	63.7	80.5	25.3	5217	95.5	6.3
	1140	2	590	2	241.1	2.00	68.1	64.1	67.6	94.0	29.0	5167	94.5	5.1
	1208	2	591	2	242.1	2.24	66.0	62.4	65.9	102.3	26.3	5009	92.5	5.2
	1435	2	592	2	-	NO DATA TAKEN - INSTR. MALFUNCTION							-	2.7
6-15-67	1528	3	VB1-593	2	219.2	2.23	62.6	58.2	62.4	82.6	28.6	5129	94.5	4.7
6-22-67	1517	3	594	2	219.7	2.12	60.2	57.1	60.4	88.3	25.8	5051	93.1	4.6
	1905	3	595	2	220.1	2.21	60.4	57.3	60.5	89.2	24.4	5056	93.5	6.6

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While the new flow spreader was being machined three additional test firings were made.

(U) In general, all test firings were nearly identical. The chamber Photocon showed random pressure oscillations of 5 to 7 psi (peak-to-peak) during the steady-state portion of the firing without any evidence of pressure spikes. The start transients were all typical showing low-frequency "chugging" of 30 to 50 cycles per second for the initial 1.0 to 1.5 seconds. Figure 14 is a reproduction of the VB1-582 oscillograph during the steady-state portion of the firing.

(U) The primary cause for lower than expected performance was attributed to the high percentage of secondary flow which was being improperly mixed with the hollow cylindrical fuel sheet. The secondary cause for low performance, as shown in the trend of increasing performance with increasing mixture ratio, was the fuel injection velocity which was selected too high at the initial design point for the propellants and mixture ratio used.

(U) The silicone rubber pintle tip was in excellent condition following 32 seconds of firing and exposure to raw oxidizer during system blowdown tests and aborted firings. Figure 15 shows the pintle tip following 14 seconds of firing and exposure to raw oxidizer while Figure 16 shows the pintle tip after firing VB1-586. After 14 seconds of firing the heat-sink thrust chamber showed markings typical of those experienced during a short duration LMDE ablative chamber firing. These markings are still in evidence in Figure 17 which shows the internal surface of the chamber after 32 seconds of firing following the timer failure during test firing VB1-586.

(U) The only significant temperature data obtained from the test program was on test firing VB1-586 during which the timer malfunctioned. The temperature data for three of the eight external chamber thermocouples is shown as Figure 18. Thermocouple locations are shown in Figure 29, Appendix II. The maximum temperature indicated was 304°F during the firing with a soak-back of 409°F approximately 8 seconds after shutdown. The paint on the exterior of the throat section showed evidence of the high temperature. Prior to this test no external heat markings were observed on the thrust chamber. During test firing VB1-586 the chamber pressure decayed approximately 1.5 percent during the final 3 seconds of the firing indicating internal wall temperatures high enough to cause thermal expansion of the throat. Post-test examination did not reveal any damage to the hardware.

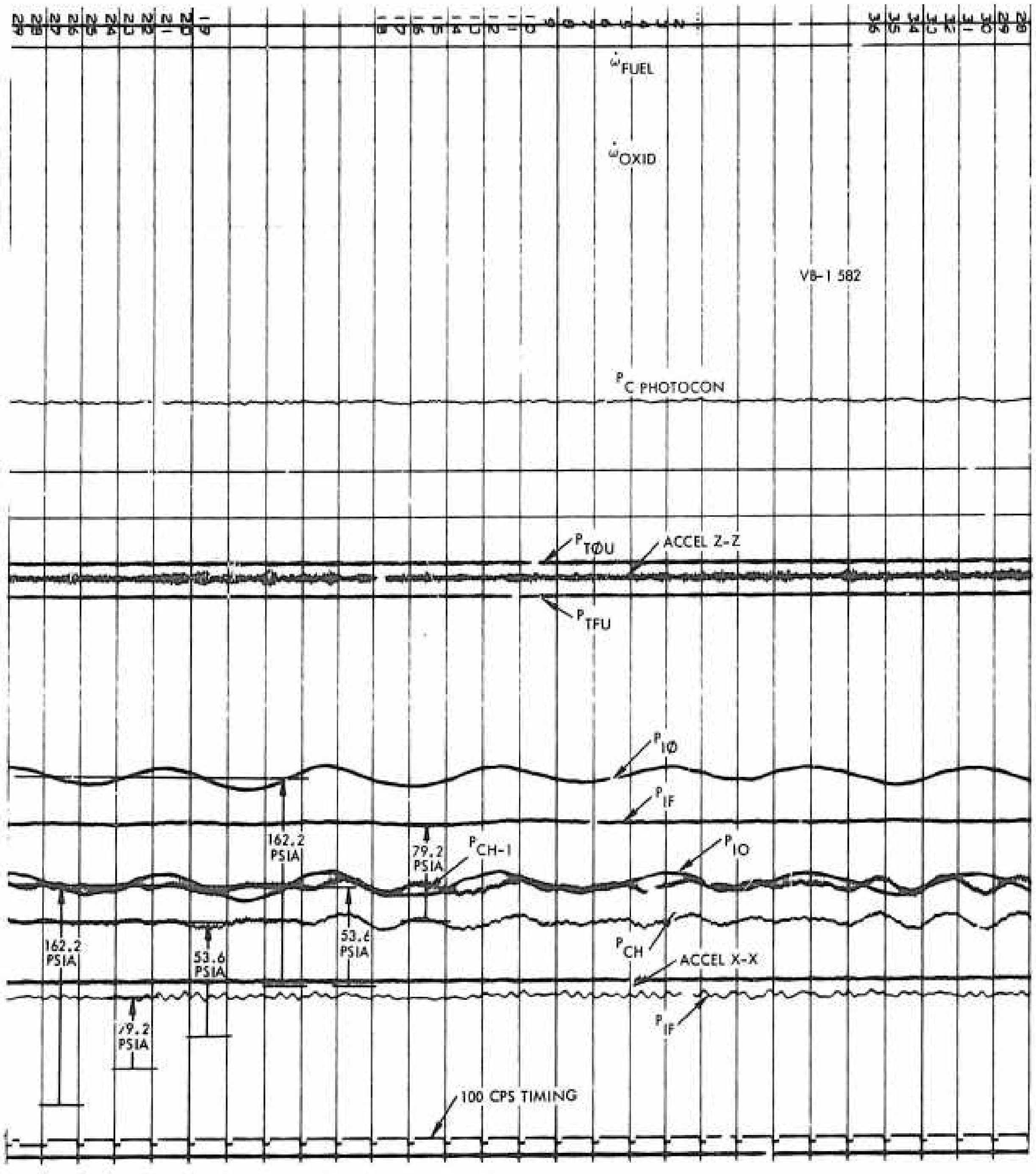

Figure 14. Oscillograph Trace of VB1-582

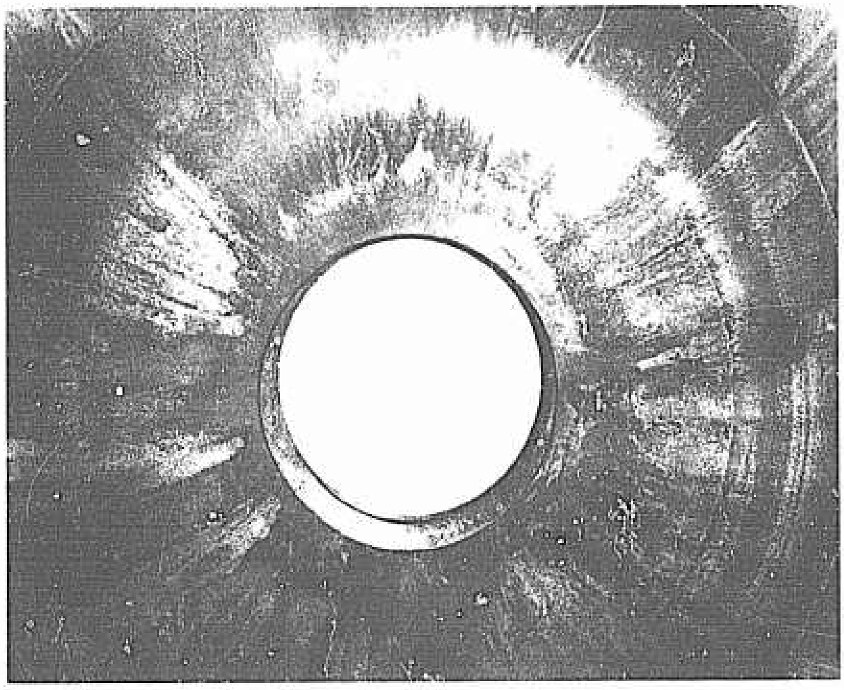

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Figure 15. Pintle Tip After 14-Second Firing and Exposure to Raw Oxidizer

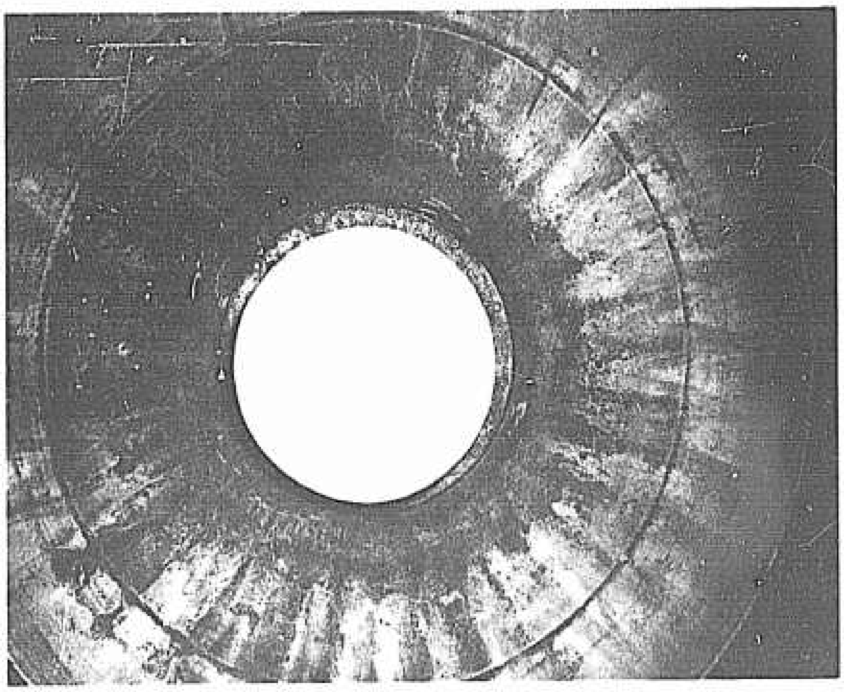

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Figure 16. Pintle Tip After Firing VB1-586

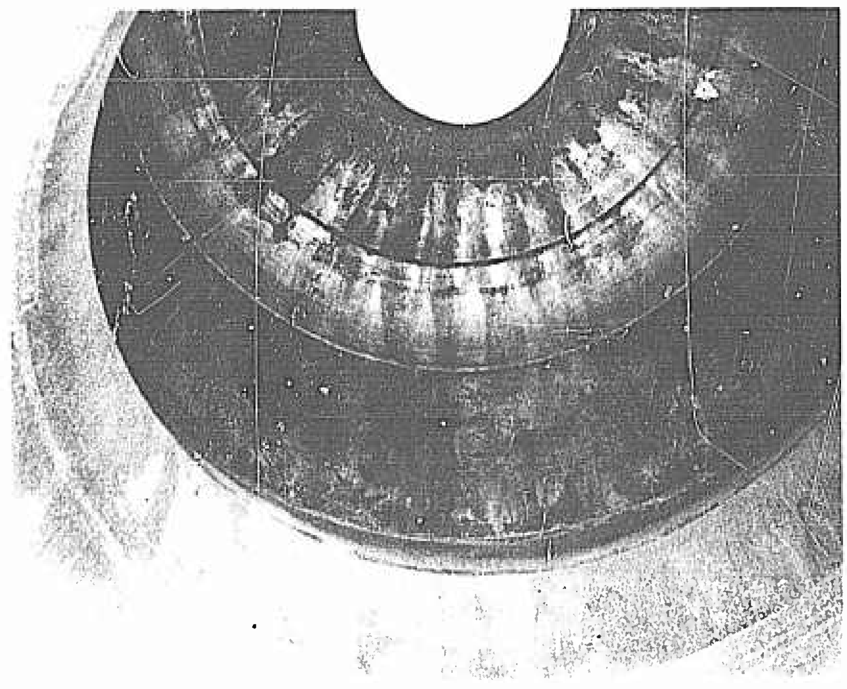

Figure 17. Thrust Chamber Internal Surface, VB1-586

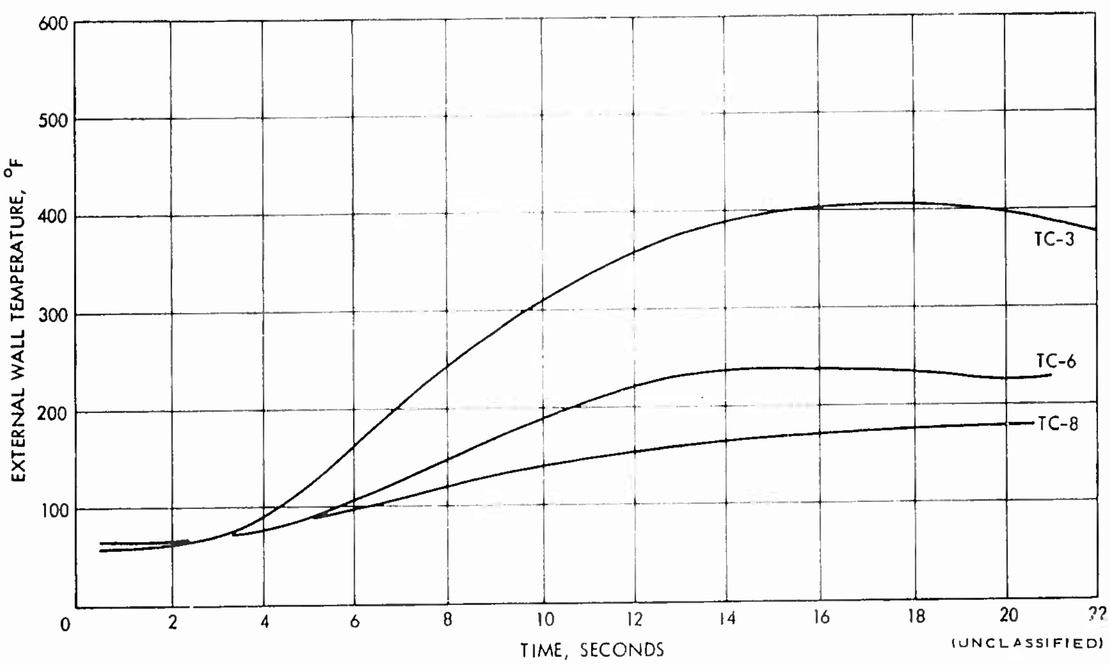

Figure 18. Temperature History, VB1-586

3.2.2 Test Series No. 2

(U) The initial test series revealed insufficient penetration of the fuel sheet by the oxidizer filaments. Therefore, the injector was modified to (1) decrease the fuel injection ΔP by increasing the injection area, and (2) decrease the percentage of secondary oxidizer flow. Following hydraulic testing of the injector to characterize the spray pattern a steel, conical pintle tip was welded to the injector pintle. The injector was then reinstalled in the TCA. The data for test series No. 2 is also tabulated in Table I, and plotted in Figure 13. As shown in Table I, the second test series consisted of three test firings at the design flow rate and covered the O/F ratio from 2.00 to 2.50, as well as two additional firings at increased flow rates to investigate the effect of total momentum. Appendix IV contains pertinent remarks and observations for each firing in the test series.

(C) The initial test firing in test series No. 2 following injector modification resulted in achievement of a performance level which was 10 percent greater than the performance level achieved with injector configuration No. 1 at the same O/F ratio. The highest combustion efficiency (95.5 percent of theoretical frozen C*) was achieved during test firing VB1-589. The 95.5 percent performance value is 12.5 percent higher than that achieved with injector configuration No. 1 at a comparable O/F ratio. The two firings at increased flow rates (VB1-590, VB1-591) both showed approximately 1 percent decrease in performance when compared with test firings at the design flow rate.

(U) The test firings of test series No. 2, plus the test firings in the Combustion Stability Evaluation program, were used to determine the applicability of the scaling concepts used to arrive at the injector configuration. The LMDE coaxial injector and the 250,000 lb_f injector have a similar number of primary and secondary oxidizer orifices with identical fuel sheet thickness/unit spacing relationships. Therefore, a simple mixing parameter comparison should show a unique comparison with respect to performance achieved at the same value of the mixing parameter.

(C) The mixing parameter used to compare the performance of the throttled 250,000 lb_f injector with the LMDE is given as Equation (1).

$$\text{Mixing Parameter} = \frac{1}{\dfrac{\rho_f V_f^2 (C_d A)_f}{\rho_o V_o^2 (C_d A)_o} \times K} \qquad (1)$$

where

	ρ	=	density, lb/ft^3
	V	=	velocity, ft/sec
	C_d	=	discharge coefficient
	A	=	area, ft^2
	K	=	empirical factor
Subscript	f	=	fuel
Subscript	o	=	oxidizer

K is an empirical factor to account for side interaction of fuel sheet with the oxidizer filaments. This factor is normally less than unity. Figure 19 shows the result of such a comparison. Typical LMDE performance levels are shown as a function of mixing parameter for both 100 and 65 psia while the data for this program is at a nominal 60 psia. Both injectors peak at or near the same value of the mixing parameter. The lower performance for the throttled 250, 000 lb_f injector may be attributed to a number of factors. Such things as operation at reduced chamber pressure, the somewhat lower reactiveness of the N_2O_4/UDMH propellant combination, and the fact that second order scaling effects have not been explored to any extent. For example, the percent secondary flow may need some additional adjustment.

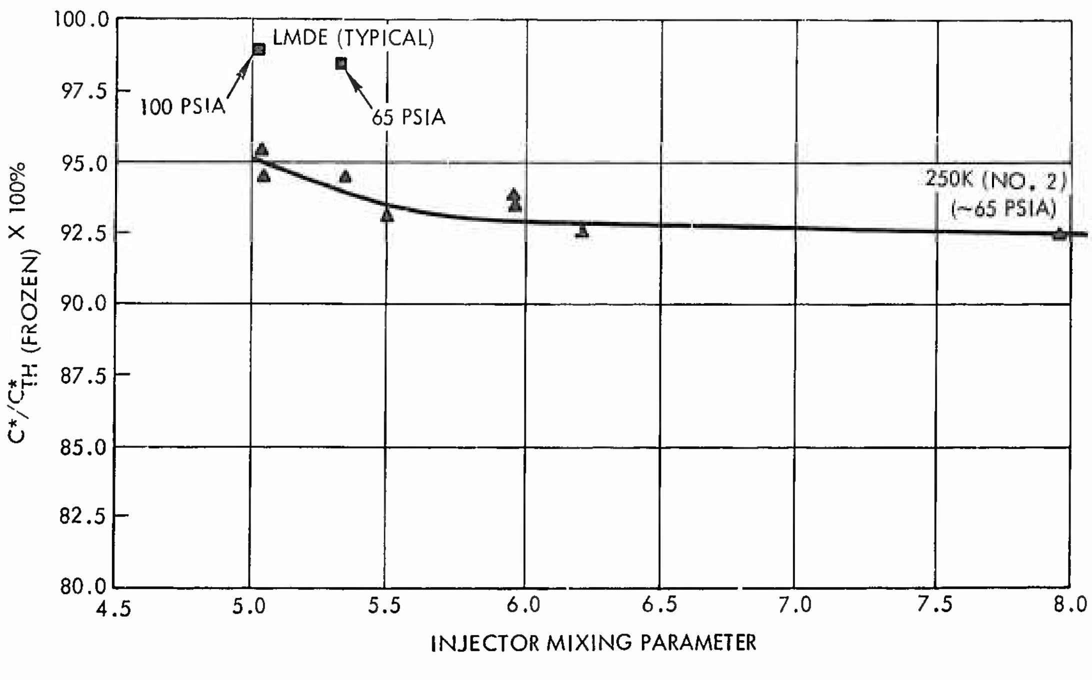

Figure 19. Injector Scaling Comparison

(U) In general, the test firings in test series No. 2 were quite similar to the firings in the initial test series. The start transients were characterized by "chugging" at 30 to 50 cps for nearly 0.5 second. The chamber Photocon showed random pressure oscillations of 5 to 10 psi (peak-to-peak) during the steady-state portion of the firing without any evidence of pressure spikes.

(U) Examination of the test hardware prior to the initial test firing in the Combustion Stability Evaluation program showed the test hardware to be in excellent condition following nearly 65 seconds of firing. The steel, conical pintle tip was essentially unmarked and the thrust chamber did not show any abnormal heat patterns. Both the pintle tip and thrust chamber are shown in Figure 20.

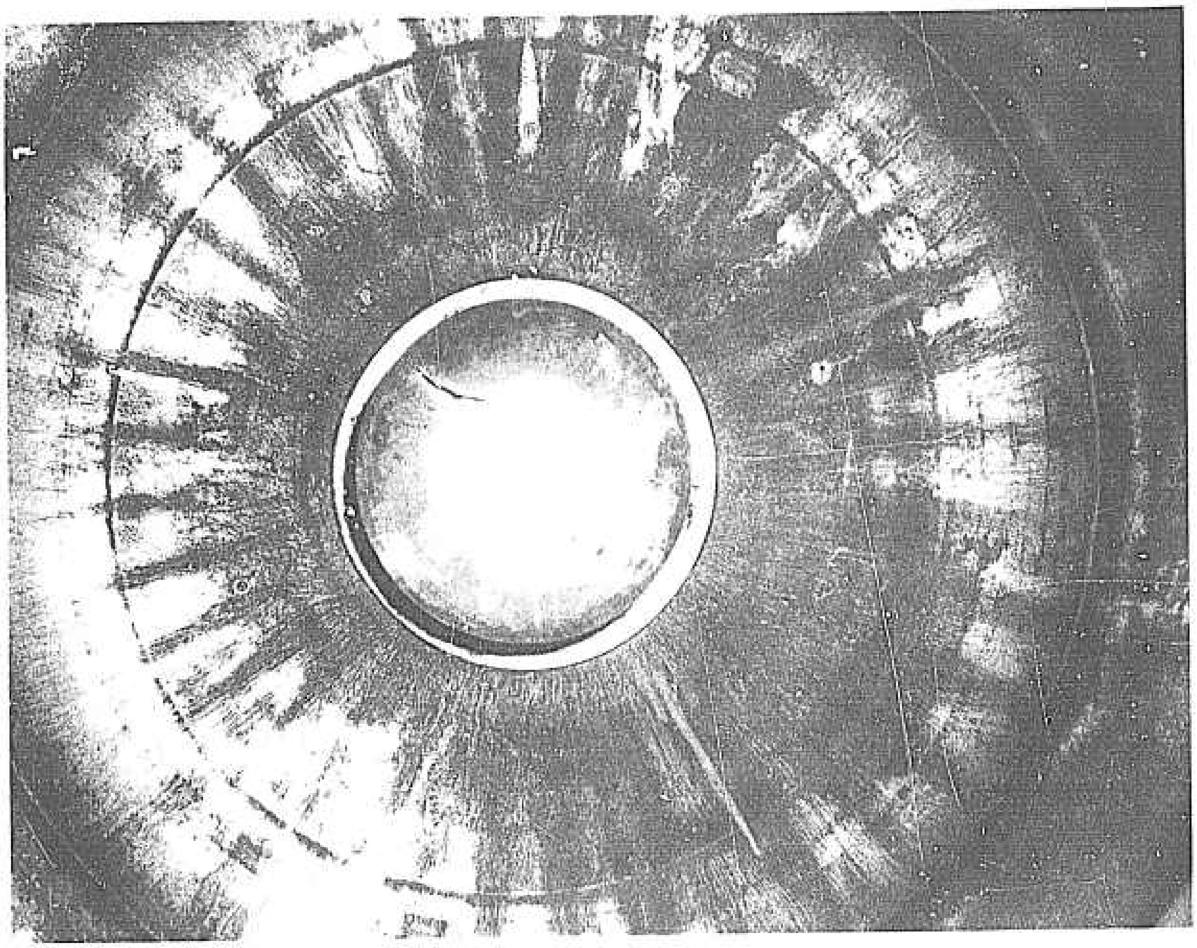

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Figure 20. Steel Conical Pintle Tip and Thrust Chamber

3.2.3 Combustion Stability Evaluation

(C) Following achievement of performance levels greater than 90 percent with injector configuration No. 2, a combustion stability evaluation test series in satisfaction of paragraph 2.7 of the contract (Modification No. 3) was undertaken. The initial test firing in the series employed a 30-grain (TNT equivalent) nondirectional explosive charge of the configuration shown in Figure 21. This charge was installed in the chamber wall, extending approximately 1.5 inches into the chamber at a point 3.5 inches below the propellant impingement plane. High response Photocon pressure transducers were flush-mounted in the chamber wall as shown in Figure 22. The timer was set to trigger the explosive charge approximately 3 seconds after signal. The oscillograph shows the explosive charge being detonated at 2.95 seconds after start signal. Details of the test firings in the combustion evaluation test series are given in the following paragraphs.

Test VB1-593

(U) The test firing was targeted for an O/F ratio of 2.25 at the nominal total flow rate of 220 pounds per second. The start transient for this firing was typical of all prior firings showing some "chugging" at 50 cps. The chamber Photocon PcP-1 (see Figure 22) was lost 0.965 second after the start signal. This Photocon was presumably damaged in the prior firing VB1-592. The second chamber Photocon showed a chamber pressure variation of 6 psi peak-to-peak prior to detonation of the explosive charge. Low amplitude 100 cps variations were observed in the fuel injection pressure trace and 30 cps low amplitude variations were observed in both the oxidizer injection pressure trace and Taber chamber pressure trace. The second chamber Photocon was "lost" when the explosive charge was detonated when the Photocon amplifier became saturated. The "overpressure" generated by the 30-grain (TNT equivalent) explosive charge was estimated to be 400 percent. A "playback" was made of the high speed tapes of the following parameters: PFUV, PFDV, PIF. PcP-2, PcP-1, PØDV, and PIØ. Examination of the tape playbacks show the pressure wave surge in PIØ, PØDV, and PØUV following the detonation and a second peak about 30 milliseconds later. The surges in PØUV and PØDV are then essentially damped out and PIØ appears to follow the head-end chamber pressure fluctuations. Playbacks of PFUV, PFDV, and PIF show extreme excursions in PFDV following the detonation of the explosive charge. The fuel "cavitation" bubble is apparently being collapsed, causing a decrease in flow which results in a chamber pressure decay and high O/F ratio. As the P_c drops the fuel venturi again cavitates and flow increases, increasing P_c rapidly and feeding back to the fuel venturi. This low frequency (40 to 60 cps) feed system controlled process continued for about 1.7 seconds without stabilizing after the explosive charge was detonated.

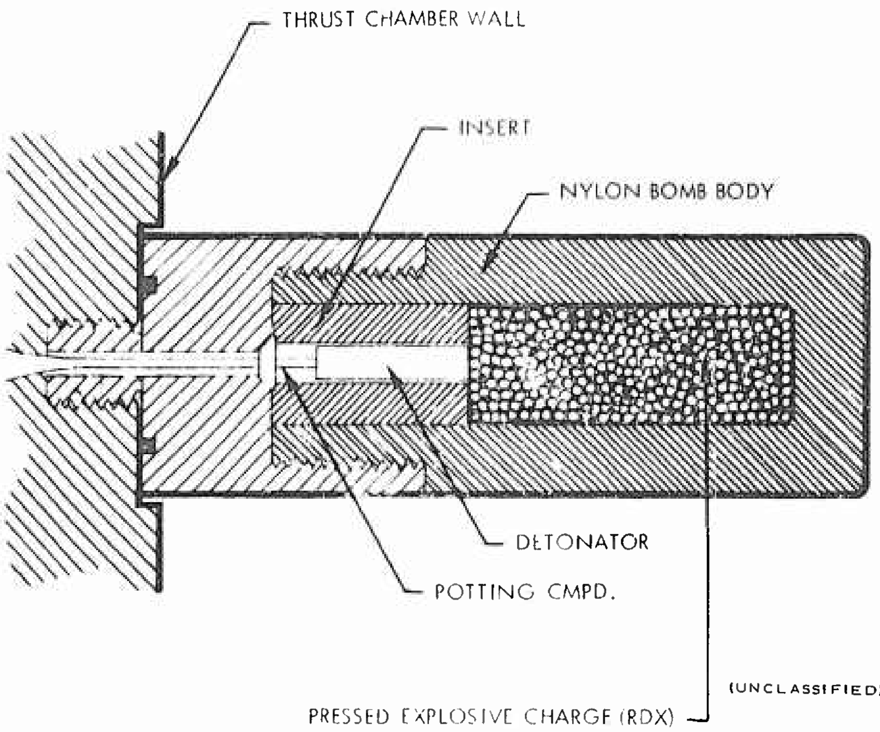

Figure 21. Explosive Charge Configuration

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Figure 22. Instrumentation Installation

(U) Examination of the test hardware following the test firing did not reveal any damage to the thrust chamber, injector or test stand. Examination of the interior of the thrust chamber disclosed that the explosive charge had been located in a fuel-rich combustion zone which may have contributed to the excessive overpressure. There was no evidence of increased heat transfer to the chamber wall.

(U) Analysis of the test data, including Fastax movie film coverage, indicated that the low frequency "chugging" was being driven by the fuel side of the feed system. In order to "harden" the feed system against coupling with pressure surges in the combustion chamber, the fuel cavitating venturi flow area was increased so that the design flow rate could be obtained at a lower inlet pressure than the 230 psia required on prior tests. This had the effect of decreasing the size of the cavitation bubble resulting in an increase in fuel feed line resonant frequency from a value near the 40 to 50 cps observed to a value closer to the 150 to 190 cps calculated for the actual test system feed lines. This led to uncoupling the fuel feed system from pressure surges in the combustion chamber.

(U) A checkout firing (VB1-594) was made prior to the second combustion stability test to determine the effect of the increased area fuel venturi on normal operation. In addition measures were taken to protect the high response pressure transducer at the time of charge detonation. Figure 23 shows the explosive charge and Photocon location for the second combustion stability evaluation test firing. A Kistler high response pressure transducer (Model 616A) was mounted in the chamber head 90 degrees removed from the explosive charge location. Figure 24 is a schematic representation of the charge and instrumentation location.

Test VB1-594

(U) The test firing was targeted for an O/F ratio of 2.20 at a total flow rate of 220 pounds per second for the purpose of facility and instrumentation checkout prior to the second combustion stability evaluation test firing. The start transient for this firing was typical showing a low frequency "chugging" start at 30 cps for about 0.5 second. The start transient is shown in Figure 25. Both injection pressures were smooth and the chamber pressure variation (as recorded with the Kistler transducer) was approximately 7 psi, peak-to-peak. The O/F ratio achieved during the firing was slightly low (2.12) as a result of higher than normal fuel flow. The measured performance level fell within the limits of that measured on previous firings with this injector configuration.

Test VB1-595

(U) The test firing employed a 20-grain (TNT equivalent) explosive charge which was signalled to detonate at 2.6 seconds after the start timer signal. The target run conditions were identical to test firing VB1-594; both target O/F and total flow rate were achieved. The start transient and steady-state portion of the firing prior to detonation of the explosive charge were essentially the same as test firing VB1-594. Figure 26 is a reproduction of the oscillograph (number 1) from just prior to charge detonation to 150 milliseconds after detonation. A large pressure surge can be observed in the oxidizer injection pressure trace at the time of the

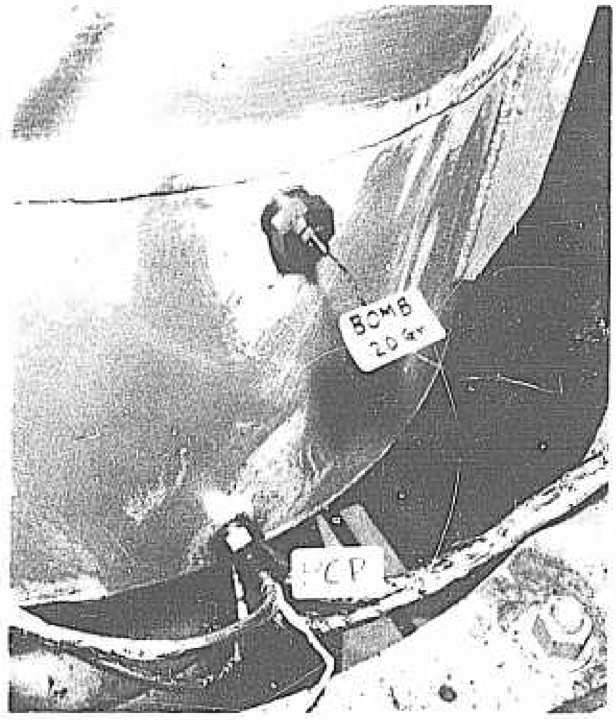

Figure 23. Explosive Charge and Photocon Location

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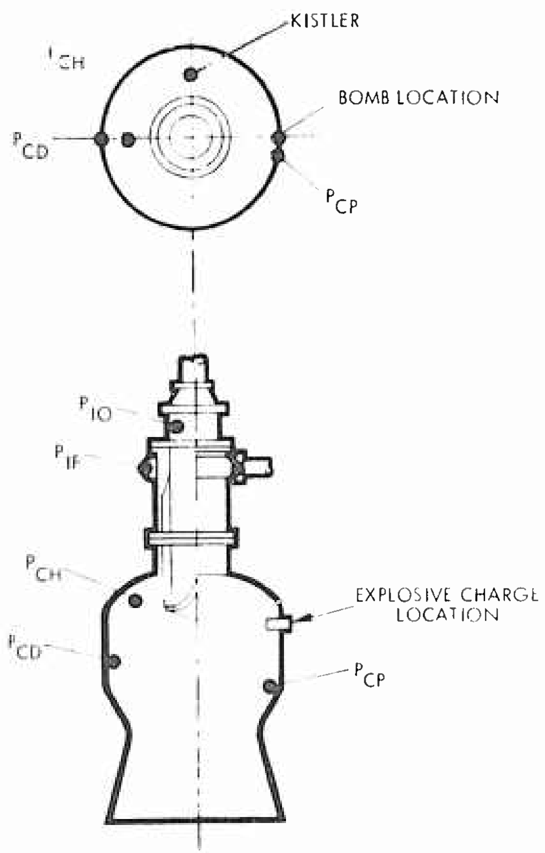
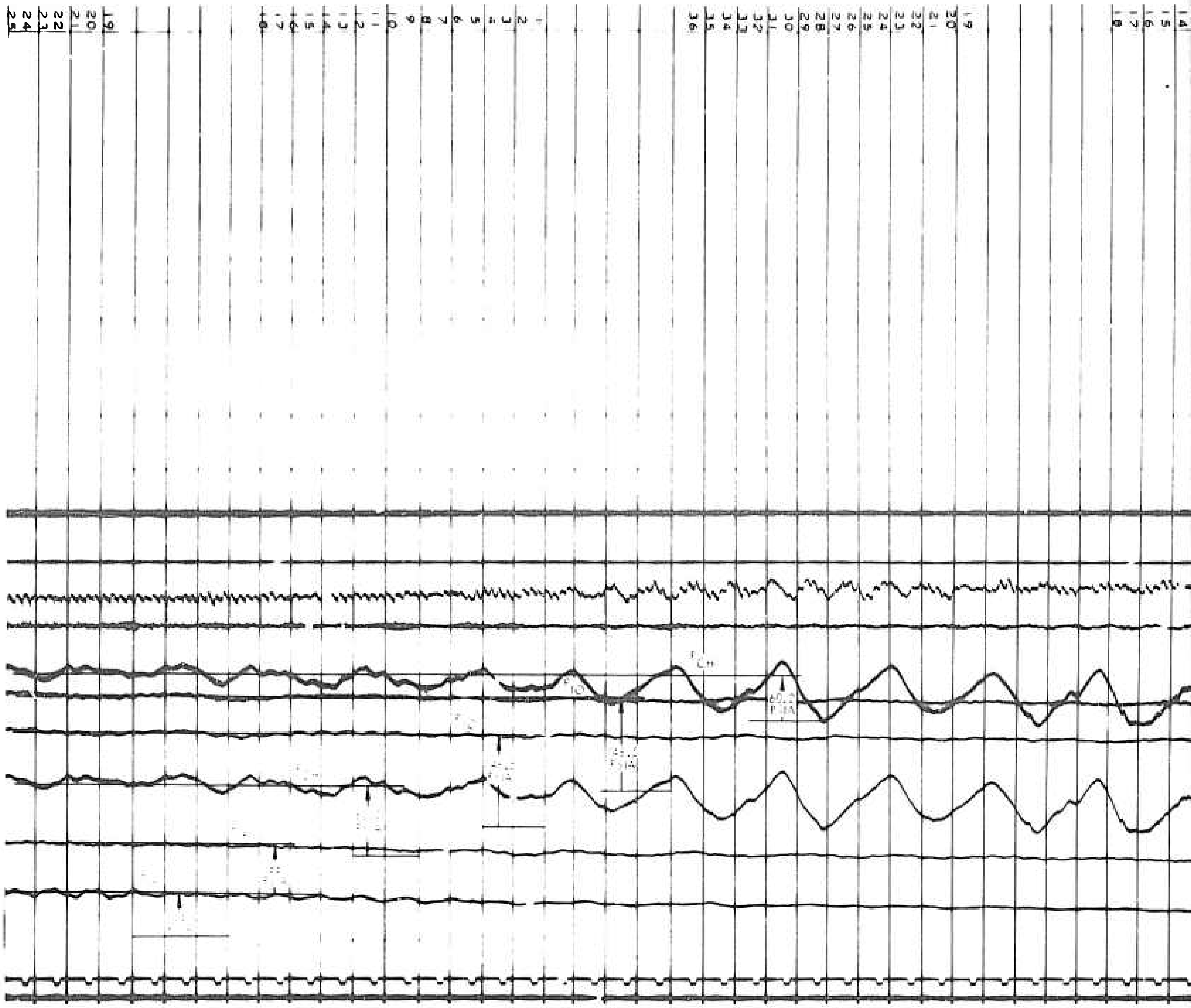


Figure 24. Schematic Representation of Explosive [illegible] and Instrumenta[illegible]tion



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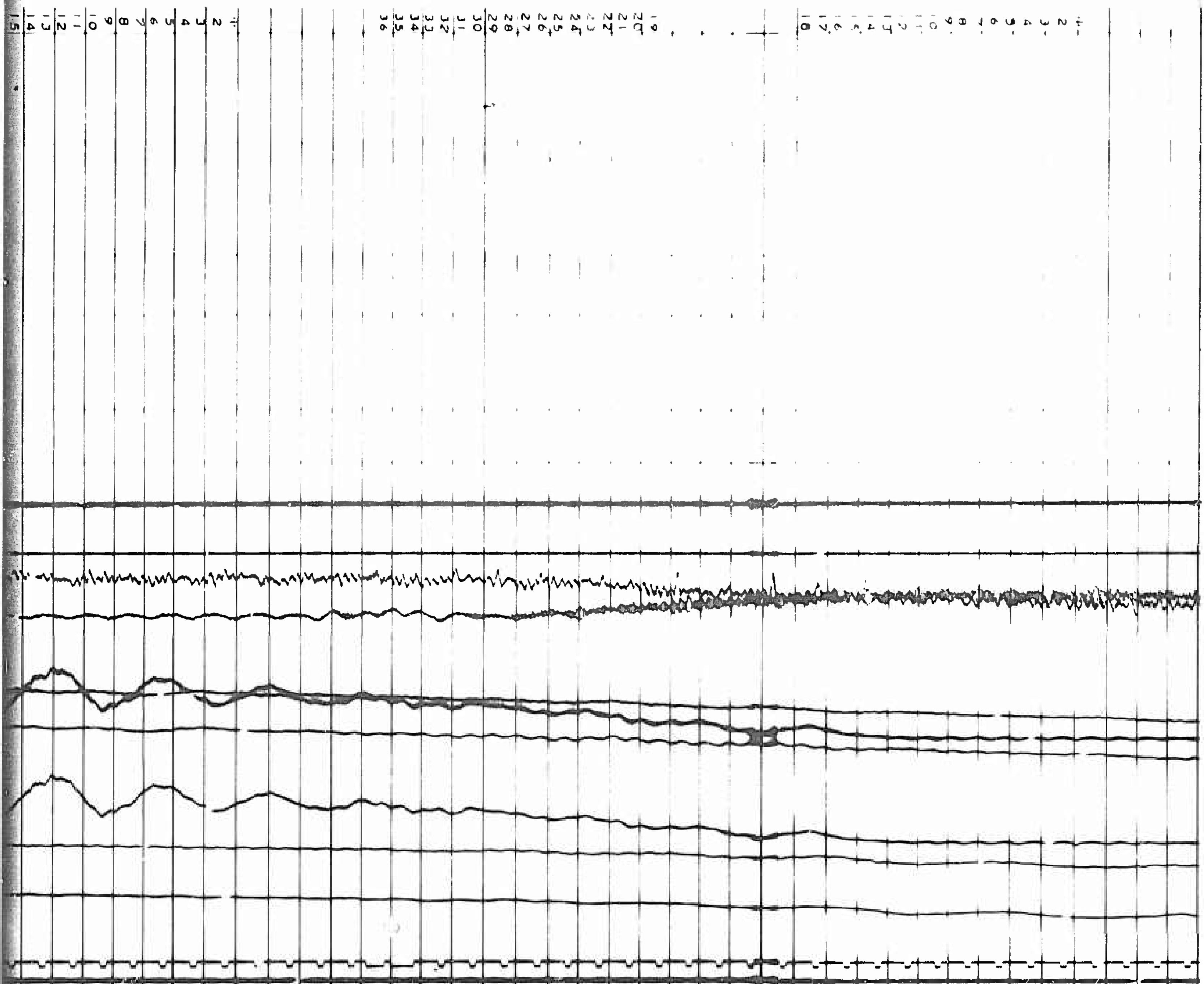

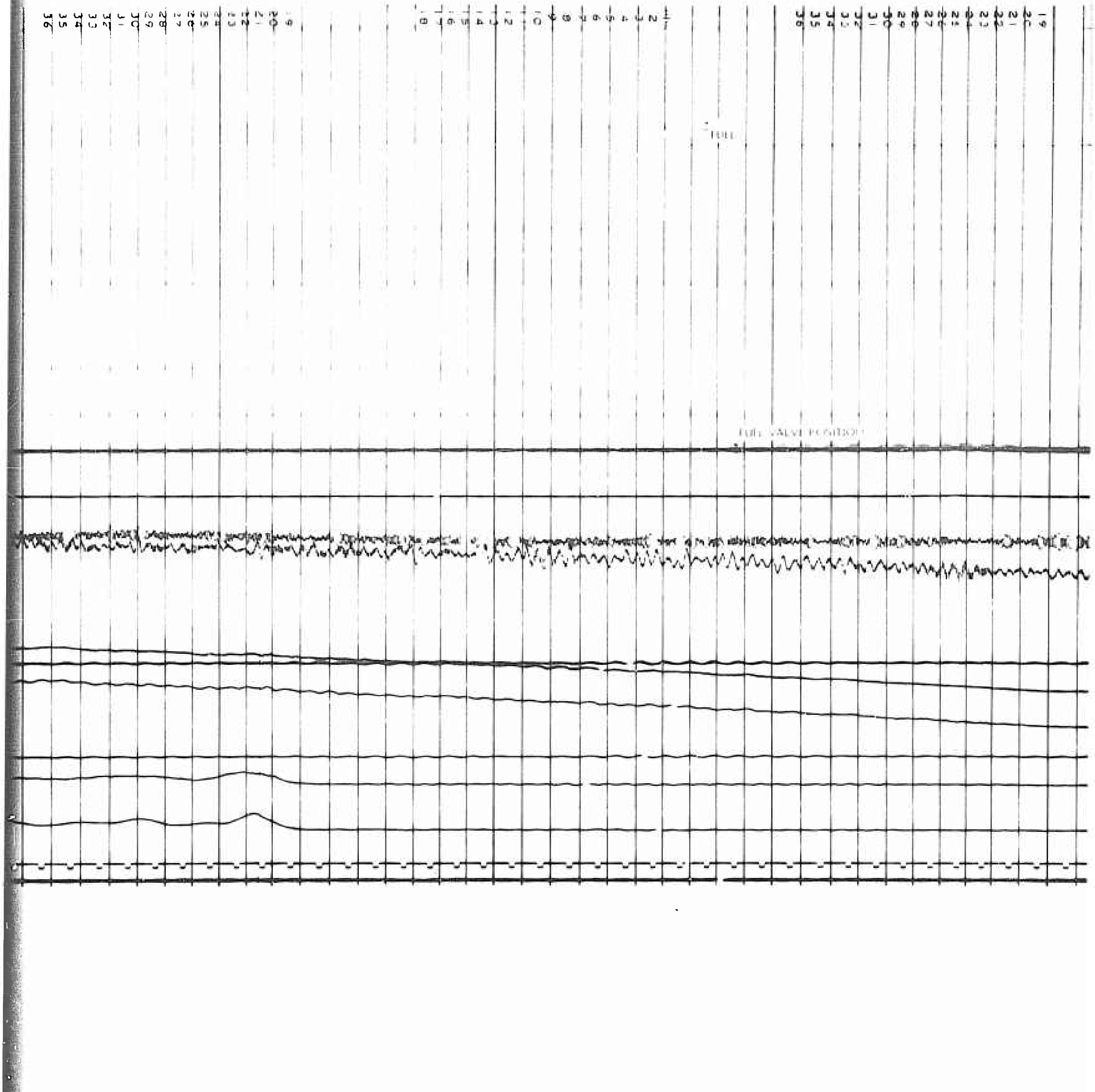

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Figure 25. VB1-594 Start Transie
Oscillograph Reproduc

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Figure 25. VB1-594 Start Transient Oscillograph Reproduction

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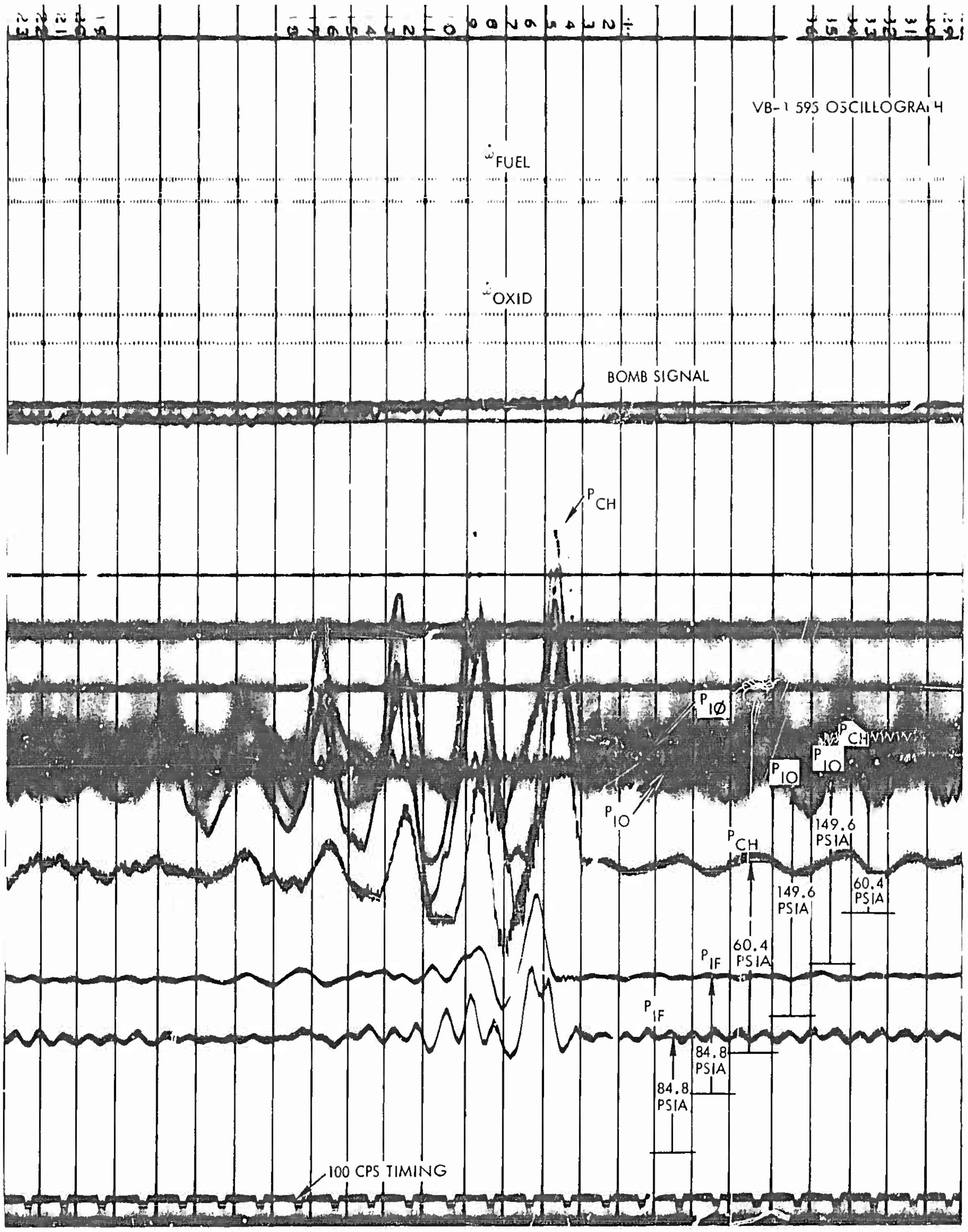

Figure 26. VB1-595 Oscillograph (No. 1) from Before Charge Detonation to 150 msec After Detonation

explosive charge detonation and recovery to normal operation occurs within 100 milliseconds. The playback of the high speed tape showing the Kistler transducer, Photocon transducer, and X-X accelerometer for the same time period is reproduced as Figure 27. Both the Kistler and the Photocon pressure transducers show pressure surges of 150 psi above operating pressure. This is equivalent to a 250 percent "overpressure." Figure 27 shows that the complex acoustic wave which was generated has been damped out in 15 milliseconds and, although some indication of the 40 to 50 cps test plumbing resonance still remains, the feed system recovery is essentially complete within 40 milliseconds.

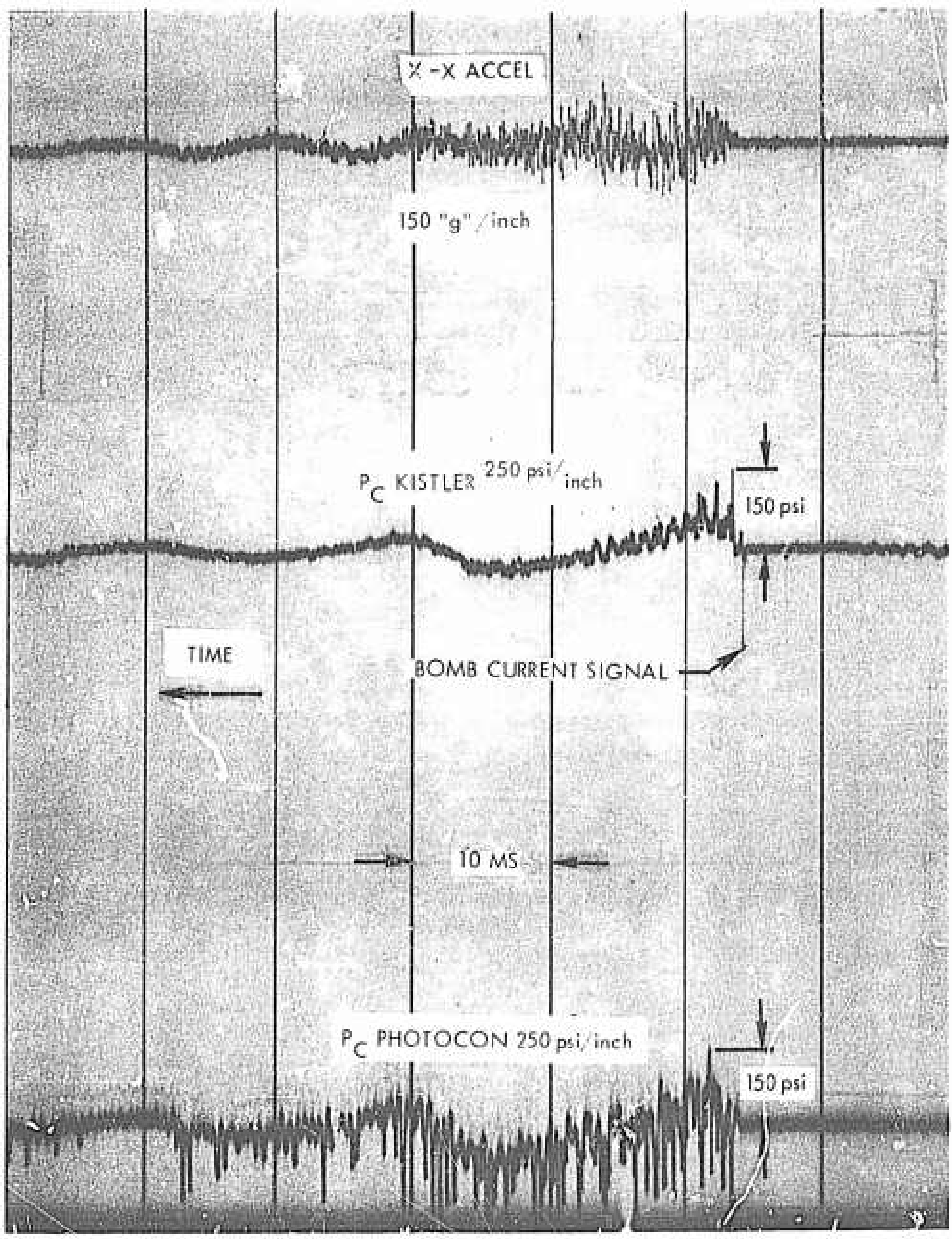

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Figure 27. Test VB1-595, Oscillograph of High Response Transducer Showing Explosive Charge Detonation

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

(U) The conclusions reached while performing the program of experimental engine firings are summarized as follows:

1) The centrally located, coaxial injector rated at 250,000 lb_f thrust operated at 50,000 lb_f thrust is dynamically stable when subjected to explosive charges which produce "overpressures" in excess of 200 percent of the normal operating pressure.

2) The scaling concepts used to scale the LMDE coaxial injector over a 25-to-1 range appear promising.

3) High thrust injectors may be designed with a minimum of precision tolerances for fabrication using conventional industrial fabrication techniques and will produce acceptable performance.

(U) The following work should be undertaken for the purpose of obtaining basic engineering data which will allow scaling of the coaxial injector design for use in multimillion-pound-thrust liquid rocket engines of maximum cost/effectiveness.

1) Engine testing at the rated thrust level (250,000 lb_f) to demonstrate performance and inherent dynamic combustion stability.

2) Experimental testing of low-cost combustion chamber liners to determine the applicability of such materials for very large rocket engines. At least two candidate materials (SOC-CO K742HT and Dow-Corning 93-069) are now available. Testing of these materials in a 40-inch-diameter chamber would allow a fair assessment of the fabrication problems which might be encountered in full-size thrust chambers.

3) Engine testing of a low-cost LITVC to delineate problems, i.e., (1) protection of the injection valve seat from the hot, expanding combustion gases, and (2) behavior of the low-cost nozzle insulation in an oxidizer- or fuel-rich combustion environment.

APPENDIX I

FACILITIES

The test program was carried out using the facilities at the Vertical Engine Test Stand (VETS), at the TRW Capistrano Test Site (CTS). VETS has four vertical engine test stands, A1, A2, B1, and B2 each currently rated at 50,000 pound thrust level. Stands A1 and A2 are equipped with 2:1 diffuser, steam ejector systems which permits choked-flow operation of LMDE at chamber pressures as low as 8 psi. Stands B1 and B2 are utilized for sea-level testing.

(U) The test stand has four propellant run tanks, viz.: two 1000-gallon fuel nks (750 psi working pressure), two 1000-gallon oxidizer tanks (750 psi working pressure). Tankage, valving, and lines are such that they can be interconnected for extended duration engine tests. Safety features of the propellant feed system include pressure relief valves and burst diaphragms. The VETS has its own nitrogen cascade system which is used for fuel and oxidizer pressurization and engine purges.

(U) Test stand B1 (outboard sea-level position) was utilized for the 15 test firings in the test program. The modifications to the B1 position required to carry out this program have been described previously. Figure 28 is a schematic representation of the propellant feed system from the run tanks to the fire valves on the engine. Cavitating venturis were installed in both the oxidizer and fuel lines as shown in Figure 28. The oxidizer venturi inlet was located approximately 10 feet upstream of the oxidizer fire valve while the fuel venturi inlet was approximately 4 feet upstream of the fuel fire valve. Both fuel and oxidizer lines were equipped with high-point bleeds which dumped overboard. Filters were not used in the propellant feed system.

(U) The pressurization system for each of the run tanks is not shown in the schematic. As noted previously, each tank was pressurized from a mobile high-pressure GN_2 storage trailer through large diameter piping and Series 400 Grove pressure regulators.

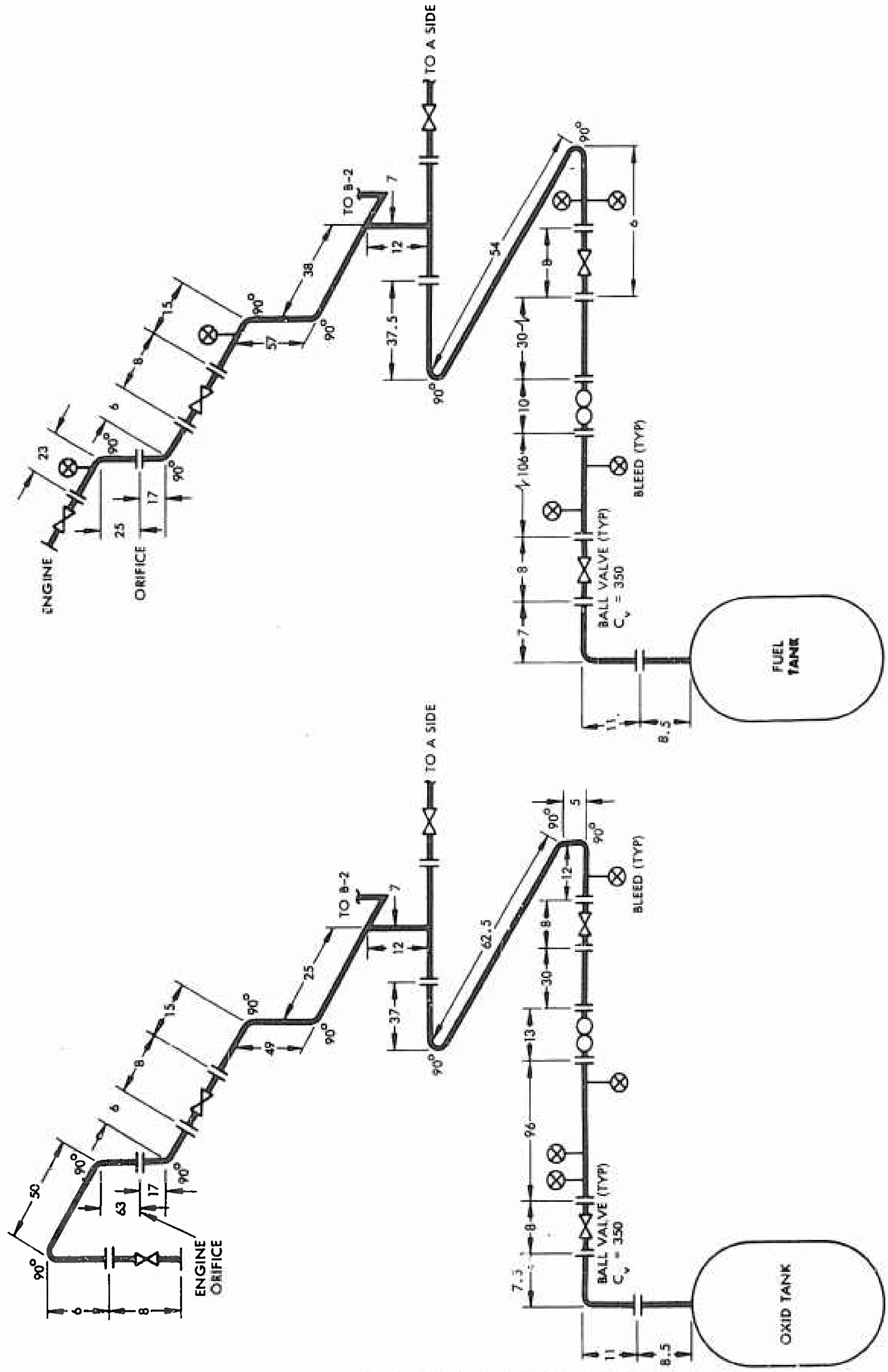

Figure 28. Schematic Representation of Propellant Feed System

APPENDIX II

INSTRUMENTATION

(U) Multiple instrumentation was maintained on all critical pressure parameters. The instrumentation required throughout the program is shown in Table II. Table III presents the instrumentation configuration list for test firing VB1-594. Dual measurements were made of head-end chamber pressure and downstream pressure, as well as oxidizer and fuel injection pressures. Pressure measurements were obtained with Taber-Teledyne bonded strain gage transducers. These transducers were dead-weight calibrated in the Capistrano Test Site (CTS) Metrology Laboratory prior to initiation of the test firing programs.

(U) Flow rate measurements were made with turbine-type flowmeters manufactured by Potter (fuel side) and Fischer-Porter (oxidizer side). Propellant temperatures were measured in the flowmeter sections for density determination. Figure 29 shows the instrumentation locations utilized throughout the program's test series.

(U) Chromel-alumel thermocouples were attached to the external surface fo the thrust chamber as shown in Figure 30. The thermocouples were only used as an indication of local overheating and were not intended to be used for heat flux measurements.

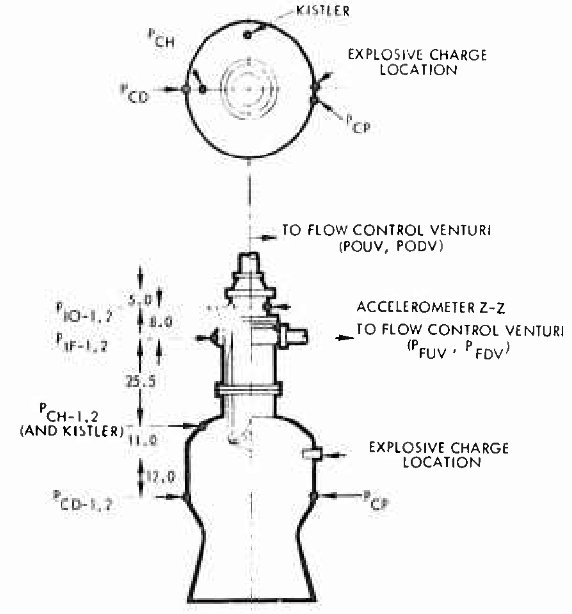

Figure 29. Explosive Charge and Instrumentation Locations

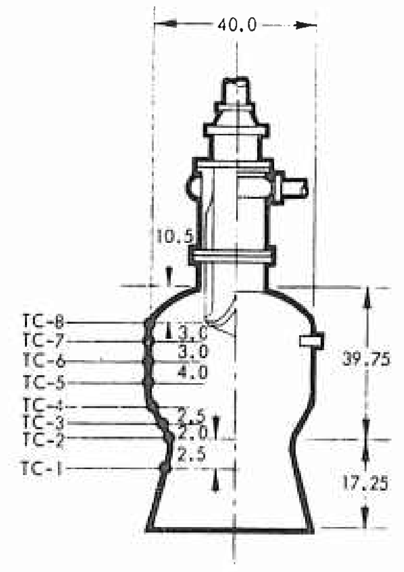

Figure 30. Thermocouple Identification and Location

Table II. Test Instrumentation Requirements

Symbol	Parameter	Range	Osc.	Strip Chart
$\dot{\omega}$ox	N_2O_4	0-1000 gpm	X	X
$\dot{\omega}$f	UDMH Flow	0-1000 gpm	X	X
Tox	N_2O_4 Flowmeter Temp.	0-150°F		X
Tf	UDMH Flowmeter Temp.	0-150°F		X
PTox	N_2O_4 Ullage Pressure	0-500 psi		X
PTf	UDMH Ullage Pressure	0-500 psi		X
Pouv	N_2O_4 Cavitating Venturi Inlet Pressure	0-500 psi	X	X
Pfuv	UDMH Cavitating Venturi Inlet Pressure	0-500 psi	X	X
PIO-1, 2	N_2O_4 Injection Pressure	0-250 psi	X	X
PIf-1, 2	UDMH Injection Pressure	0-250 psi	X	X
Pch-1, 2	Chamber Pressure, Head-End	0-100 psi	X	X
Pcd-1, 2	Chamber Pressure, Downstream	0-100 psi	X	X
Tch-1, -8	Chamber Temperature	0-2000°F		X
Pcp	Chamber Pressure, Photocon	0-1000 psi		X
ACCELZ-Z	Accelerometer	0-300 g	X	
Pcp-2	Chamber Pressure, Downstream (Photocon)			

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(U) Accelerometers were mounted on the injector to indicate vibration levels in all three planes. Both Photocon and Kistler high response pressure transducers were used during the test program. The Photocons used were model 352A, water-cooled, with flame shield. The Kistler transducer employed on firings VB1-594 and VB1-595 as a model 616A which is water-cooled.

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INSTRUMENTATION CONFIGURA

RUN NO. V[illegible] 1 5?4

HEAD END NO. B2

PAGE 1 OF 1

DURATION ____________ SEC. ________

DIGITAL

ITEM	NAME	S/N	P.E.	CHANNEL	CAL	AMP	AMP SET	STRIP CHAR	DEFL	GALVO	DEFL	POS	TYPE	D TA
1	[illegible] -1	[illegible]	150.93	1	2	1	6.04	1	60.4	1	2.4			E
2	[illegible] -2	01106632[illegible]1	[illegible]6.77	2	3	2	9.08	25	90.8	6	[illegible]			L
3	[illegible] E-1	01106A312	150.75	3	2	3	6.04	2	60.4	2	2.4			L
4	[illegible] F-2	01106332[illegible]	2[illegible]3.84	4	3	4	8.95	26	89.5	7	[illegible]			L
5	P[illegible] H-1	0120[illegible]3102	75.[illegible]4	5	2	5	7.53	3	75.3	3	3.0			D
6	[illegible] -2	0120[illegible]1	7[illegible]43	6	2	6	7.54	6	75.4	4	3.0			[illegible]
7														
8	[illegible] -1	0120[illegible]2234	75.04	8	2	8	7.50	9	75.0					[illegible]
9	P[illegible] 2	[illegible]	[illegible]	9	1	9	5.02	12	50.2					C
10	P O [illegible] V	120652630	[illegible]3	10	3	10	8.02	7	80.2					C
11	[illegible] F D[illegible]	0110632265	[illegible]	11	4	11	8.64	8	86.4					C
12	P[illegible] [illegible]V	[illegible]	[illegible]7	12	2	12	8.98	10	89.8					C
13	[illegible]	[illegible]	[illegible]	13	2	13	8.73	11	87.3					C
14	PTOU	012065300[illegible]	[illegible].14	23	2	23	8.02	[illegible]	80.2	[illegible]	3.2			C
15	PTFU	0120652632	402.07	24	3	24	8.04	14	80.4	11	3.2			C
16	P[illegible] N2O	34708	240.61	21	3	21	7.99							
17	P[illegible] N[illegible]F	34547	239.15	22	3	22	7.97							
18														
19	S[illegible]-O	—	15V	P1	[illegible]	[illegible]	[illegible]			29	3.0			[illegible]
20	S[illegible]-F	—	1[illegible]	P2	1V	[illegible]	[illegible]5			30	3.0			C
21	[illegible]	3C[illegible]A3	[illegible]	F[illegible]	[illegible]	31	[illegible]	4	[illegible]	[illegible]	[illegible]			C
22	[illegible]	[illegible]-1	16[illegible]	F[illegible]	[illegible]	32	[illegible]	5	[illegible]	28	5			B
23	V[illegible] H2O			DV[illegible]		—				17	5			
24	V[illegible] H2O			DV 3		—				19	5			
25	T[illegible]	[illegible]5	5MV	RTT1	5MV	[illegible]	5.0	22	50.0					B
26	TF	1504	5MV	RTT2	5MV	[illegible]	5.0	23	50.0					L
27														
28														
29														
30	TCH-1	[illegible]	[illegible]	T-1	1[illegible]	16	5.0	15	50.0					L
31	TCH 2	[illegible]	[illegible]	T 2	[illegible]	17	5.0	16	50.0					L
32	TCH 3	[illegible]	[illegible]	T-3	[illegible]	18	5.0	11	50.0					L
33	TCH 4	[illegible]	[illegible]	T-4	[illegible]	19	5.0	18	50.0					L
34	TCH 5	[illegible]	[illegible]MV	T[illegible]	[illegible]	20	[illegible]	11	50.0					T
35	TCH 6	[illegible]	[illegible]MV	T 6	[illegible]	[illegible]	5.0	21						L
36	TCH 7	[illegible]	[illegible]	T-7	[illegible]	[illegible]	5.0	24						A
37	TCH 8	[illegible]	[illegible]MV	T 8	[illegible]	29	5.0	20	50.0					A
38	ESS													E

APPROVALS	RUN NO. ____		RUN NO. ____		RUN NO. ____	
	LEADMAN	TEST ENGR	LEADMAN	TEST ENGR.	LEADMAN	TEST

1

Table III. Instrumentation Configuration List

TATION CONFIGURATION LIST

D END NO. B2

DATE 6-21-67

DIGITAL TAPE ____ ANALOG TAPE 6

GALVO	DEFL.	POS.	TYPE	DIG. TAPE	ANALOG TAPE	C.P.	REMOTE MET.	F.S.	REMARKS
1	2.4			L 1	8-52.5			250	
6	[illegible]			L 2	9-[illegible]			250	
2	2.4			L 3	10-52.5			250	
7	[illegible]			L 4	11-52.[illegible]			250	
3	3.0			[illegible]	12-[illegible]			100	
4	3.0			[illegible]	13-[illegible]			100	
				[illegible]	9-40			100	
				[illegible]	[illegible]			[illegible]	
				C 2	11-40			500	
				C 3	12-40			[illegible]	
				C 4	13-40			500	
				[illegible]	14-40			500	
[illegible]	3.2			C-6	8-30	[illegible] 14		500	
11	3.2			C 7	9-30	[illegible] 17		500	
						VC15		300	
						VC18		300	
29	3.0			C 1	13-30				
30	3.0			C-2	14-[illegible]				
21	.5			G 1	8-70			1000	GPM = 4,248 CPS
28	5			G-3	10-70			1000	GPM = 1,948 CPS
17	5								
19	.5								
				G-1	10-22	VH-1		130°F	
				L 2	11-22	VH-2		[illegible]	
						MV 4			
						MV 5			
				L 3	12-22	VH-3		50MV	
				L 4	13-22	VH-4		50MV	
				L 5	14-22	VH-5		50MV	
				L 6	8-14.5	VH-6		50MV	
				[illegible]	9-14.5	VH-7		5[illegible]MV	
				L 8	10-14.5	VH-8		50MV	
				[illegible]	11-14.5	VH-10		50MV	
				[illegible]	12-14.5	VH-11		50MV	
[illegible]				F-4	14-30	MV-[illegible]	MH-10		

RUN NO. ____		RUN NO. ____		RUN NO. ____	
LEADMAN	TEST ENGR.	LEADMAN	TEST ENGR.	LEADMAN	TEST ENGR.

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INSTRUMENTATION CONFIGURAT

RUN NO. ______ ____________ HEAD END NO. B2

PAGE ______ OF _____ DURATION ____________ SEC. ________ DIGITAL T

ITEM	NAME	S/N	P.E.	CHAN NFL	CAL	AMP	AMP SET	STRIP CHAR	DEFL	GALVO	DEFL	POS.	TYPE	DI TA
1 ✓	P H2O OX	0120643101	120.20	14	3	14	8.01			14	3.2			
2 ✓	P H2O FUEL	0120643105	120.40	15	3	15	8.03			15	3.2			
3														
4														
5	BIS		ON-OFF	DV-1		25				V-22 H 22			7-362	D
6														
✓7	PCD1 P	5457	187.5	C-1		DY-1	47			H 3	.75		7-361	
✓8	PCD2-P	54 6	250	C-2		DY-2	39			H 7	1.0		7-361	
9	PCD3-K	13520	500	V-1	536	30	5.0			H 23	2.0		7-362	
10														
11	ACCEL XX	T 1751	300 G	C-4		CH 4	340			H 19	2PP		7-362	
12														
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APPROVALS	RUN NO. ________		RUN NO. ________		RUN NO. ________	
	LEADMAN	TEST ENGR	LEADMAN	TEST ENGR.	LEADMAN	TEST

1

ION CONFIGURATION LIST
END NO. 32

Table III. Instrumentation Configuration List (Continued)

DATE ______________

DIGITAL TAPE ______________ **ANALOG TAPE** ______________

O	DEFL	POS	TYPE	DIG TAPE	ANALOG TAPE	C.P.	REMO MET.	F.S.	REMARKS
	3.2							150	
	3.2							150	
2/2			7-362	D3	8-40	VH-1			
	.75		7-361		1-54	MH-1		1000	
	1.0		7-361		2-54	MH-2		1000	
3	2.0		7-362		3-54	MH-3		1000	
	2PP		7-362		4-54	MH-4		300G	

RUN NO. ______	RUN NO. ______	RUN NO. ______
LEADMAN / TEST ENGR.	LEADMAN / TEST ENGR.	LEADMAN / TEST ENGR.

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2

APPENDIX III

ENGINE PERFORMANCE ANALYSIS PROCEDURES

(U) This appendix describes the data reduction procedures used to reduce the raw performance data. All raw performance data were recorded on digital tape and reduced[1] by means of the SDS 935 computer on a run-to-run basis.

(U) In the absence of thrust measurement the engine performance was characterized by the use of characteristic exhaust velocity. The characteristic exhaust velocity was computed by:

$$C^* = \frac{P_o A_t g_o}{\dot{W}_t} \qquad (1)$$

where

C^* = characteristic exhaust velocity, ft/sec

P_o = nozzle stagnation pressure, psia

g_o = gravitational constant (32.137 lb_m-ft/lb_f-sec^2)

$\dot{W}_t$ = total propellant weight flow, lb_m/sec

The combustion efficiency (η_{C^*}) was computed by dividing the C^* computed from the equation by the theoretical frozen characteristic exhaust velocity at the appropriate test nozzle stagnation pressure and oxidizer-to-fuel ratio. Figure 31 shows the variation of theoretical frozen C^* for several nozzle stagnation pressures and O/F ratios. The values used in constructing Figure 31 are taken from Reference 2 plus supplemental calculations for 50 and 65 psia.

(U) Each of the parameters within the C^* equation was computed as follows. The nozzle stagnation pressure (P_o) was computed from the ratio of nozzle stagnation pressure to chamber static pressure (P_{cd}) as determined from Equation (2).

---

[1] CTS "Quick Look" and "Real Time" Performance Analysis Program, TRW Memorandum 65.9731.9-124, dated 30 August 1965.

[2] Theoretical Performance of N_2O_4/UDMH, TRW Memorandum 9732.11.65-177, dated 7 October 1965.

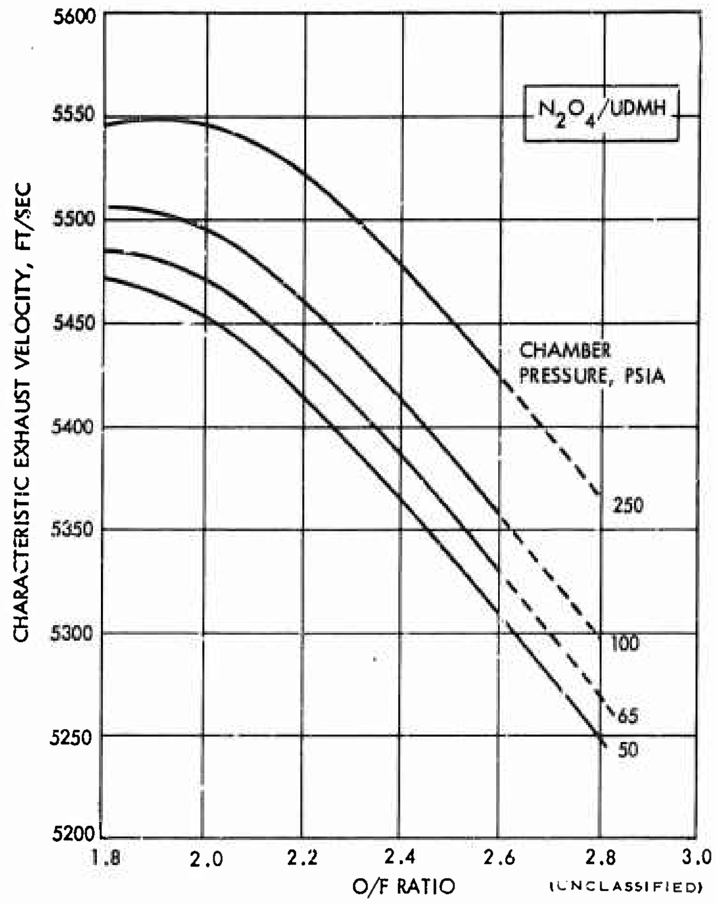

Figure 31. Theoretical Frozen Characteristics Exhaust Velocity

$$P_o/P_{cd} = 1 + \frac{\gamma}{2}\left[\frac{\alpha}{\epsilon^2 - \frac{\alpha(\gamma + 1)}{2}}\right] \tag{2}$$

in which

$$\alpha = \left[\frac{2}{\gamma + 1}\right]^{\frac{\gamma+1}{\gamma-1}} \tag{3}$$

where

P_{cd} = chamber static pressure at the nozzle enterance, psia

γ = gas specific heat ratio (γ = 1.235)

ϵ = contraction ratio

The P_o/P_{cd} ratio of Equation (2) was computed to be 1.055 for the chamber contraction ratio of 2.08. An average of two P_{cd} measurements were used

to compute P_o. The propellant flow rates were computed from the fre-quency output of the flowmeter, the calibration factor, and the propellant densities based on the measured line pressure and measured propellant temperatures. No change in flowmeters was required throughout the test program.

(U) The nozzle throat area was computed from the average of numerous throat diameter measurements taken prior to the start of the test program. Measurements taken at the conclusion of the test program indicate less than a 0.02 percent change in throat diameter. The local gravitational constant at the CTS (32.137 lb_m-ft/lb_f-sec^2) was employed in Equation (1).

APPENDIX IV

PERTINENT REMARKS—PERFORMANCE EVALUATION TEST FIRINGS

(U) This appendix contains pertinent remarks and observations for each test firing in each of the two Performance Evaluation Test Series.

TEST SERIES NO. 1

(U) VB1-581: The initial test firing was targeted at a O/F of 2.25 and 220 pounds per second total flow rate. There was no significant temperature rise on the external thermocouples and inspection of stand and TCA following the firing did not disclose any abnormal conditions. The rubber pintle tip (Dow-Corning 20-103) appeared to be essentially unmarked. The chamber Photocon showed a random pressure oscillation of 6 psi (peak-to-peak) just prior to shutdown. The chamber pressure did not reach a stabilized value during the 3.2-second firing duration. The chamber Photocon was damaged during the sequenced GN_2 purge following shutdown.

(U) VB1-582: The second test firing in the initial test series was targeted for an O/F ratio of 2.6 at 220 pounds per second total flow rate. The test firing duration was increased from a nominal 3.0 seconds to a nominal 5.0 seconds to allow for acquisition of stabilized data. The mixture ratio obtained in the test firing was slightly low (O/F = 2.53) due to a higher than normal oxidizer tank nitrogen regulator pressure drop. The chamber Photocon showed a random pressure oscillation of 7 psi (peak-to-peak) during the steady-state portion of the firing. The chamber pressure reached a stabilized value during the last 2 seconds of the 5.3-second firing. Again there was no significant temperature rise shown by the external thermocouples.

(U) VB1-583: The test firing target conditions were an O/F ratio of 2.8 at a total flow rate of 220 pounds per second. The O/F ratio and total flow rate achieved during the firing were both about 2 percent low with no significant changes in engine characteristics from the previous firing. The chamber Photocon showed a 6 psi peak-to-peak variation during the steady state portion of the firing.

(U) A thorough examination of the test stand and test hardware was made following the third test of the first test series. The silicone rubber pintle tip was in excellent condition following 14 seconds of firing and exposure to raw oxidizer during system blowdown tests. The heat-sink thrust chamber showed markings typical of that experienced during a LMDE firing. No external heat markings were observed on the thrust chamber.

(U) The fourth, fifth, and sixth firings of test series No. 1 were made following a series of difficulties with the shutdown timer and malfunction of oxidizer lead interlock microswitch. The timer had to be replaced and was reset to provide a 4.5-second test firing duration.

(U) VB1-584: This test firing was targeted for an O/F ratio of 2.0 at a total flow rate of 220 pounds per second; both conditions were achieved during the firing. The chamber Photocon showed a 6 psi peak-to-peak fluctuation during the steady-state portion of the firing.

(U) VB1-585: This firing was targeted for an O/F ratio of 2.25 at a total flow rate of 242 pounds per second to investigate the effect of increased total momentum. The O/F ratio achieved was slightly low and total flow rate slightly high. There was no increase in chamber pressure fluctuations and the performance was approximately 1.5 percent higher than the baseline firing (VB1-581).

(U) VB1-586: This firing was targeted for an O/F ratio of 2.53 (duplicating the O/F ratio of VB1-582) at a 10 percent increase in total flow rate. The chamber pressure Photocon showed a 7 psi (peak-to-peak) fluctuation. As a result of malfunction of the shutdown timer the test firing duration was 9.5 seconds. This failure was similar to that experienced during the electromechanical checkout prior to test VB1-584. The external thermocouples indicated a temperature of 304°F at the throat just after shutdown with a soak-back to 409°F at 8 seconds after shutdown. The chamber pressure dropped approximately 1.5 percent during the last 3 seconds indicating internal wall temperatures high enough to cause thermal expansion of the throat. Examination of the hardware did not disclose any abnormal condition. The silicon rubber pintle tip was intact and the chamber showed the typical markings. The external paint at the throat section showed evidence of the high temperature.

TEST SERIES NO. 2

(C) VB1-587: The initial test firing in test series No. 2, following injector modification, was targeted for the design conditions of an O/F ratio of 2.25 and a total flow rate of 220 pounds per second. The mixture ratio achieved during the firing was approximately 4 percent low. The performance increased more than 10 percent over that obtained with the initial injector configuration at the same O/F ratio. The chamber pressure Photocon showed a 5.0 to 7.5 psi peak-to-peak variation.

(U) VB1-588: This test firing was targeted for an O/F ratio of 2.55 at a total flow rate of 220 pounds per second. The mixture ratio achieved was 2 percent low (O/F = 2.50) and the weight flow rate was slightly more than 1 percent high (223.0). The chamber Photocon pressure transducer showed a 5 to 10 psi fluctuation throughout the steady-state portion of the firing at 40 cycles per second. The performance increase at higher mixture ratio for injector configuration No. 2 was somewhat less than the increase achieved at the lower O/F ratio.

(C) VB1-589: This test firing was targeted for an O/F ratio lower than design (O/F = 2.00) at the nominal total flow rate. The highest combustion efficiency (95.5 percent of theoretical frozen C*) was achieved during this firing. This is nearly 12.5 percent higher than that achieved at a comparable O/F ratio with injector configuration No. 1. The chamber Photocon showed a variation of 5 to 8 psi (peak-to-peak) throughout the test firing.

(U) VB1-590: Test firing VB1-590 was the first test of injector configuration No. 2 targeted for 110 percent of the nominal flow rate to investigate the effect of total momentum level. The target O/F ratio was 2.00. The performance level decreased approximately 1 percent when compared with firing VB1-589. The chamber pressure oscillation was nearly identical with that of VB1-589 showing some feed system disturbance of 50 to 60 cycles per second.

(U) VB1-591: The targeted O/F ratio for this firing was 2.25 at 110 percent of nominal flow rate to investigate the effect of total momentum level at a second momentum ratio. Again, a 1 percent decrease in performance level was observed. The chamber pressure oscillations were 5 psi (peak-to-peak) as recorded with the flush-mounted Photocon.

(U) VB1-592: The targeted conditions for this firing were an O/F ratio of 2.25 at a total flow rate of 198 pounds per second. The firing was terminated 2.6 seconds after fuel flow initiation when there was an instrumentation malfunction which indicated low oxidizer flow. No data was taken as the chamber pressure had not stabilized.

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5 AUTHOR(S) (Last name, first name, initial)

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY
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13 ABSTRACT

This report covers an experimental test program to determine the scalability of the LMDE centrally located, coaxial injector to much higher thrust levels than previously tested. A 250,000 lbf thrust, 300 psia chamber pressure Thrust Chamber Assembly (TCA) was fabricated and tested at a reduced thrust level of approximately 50,000 lbf thrust. The TCA design consisted of a centrally located coaxial injector, based upon the LMDE design, and heat sink combustion chamber. Performance levels in excess of the contractual requirements were achieved. Dynamic combustion stability test firings, employing nondirectional explosive charges, verified the combustion stability characteristics of the coaxial injector.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
liquid propellant engine						
injection						
stability demonstration						
low cost						

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